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propagation of UHECRs in cosmic magnetic fields

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in collaboration with

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motivation

origin

- where do UHECRs come from?
- how are the sources distributed?
- how can particles be accelerated to such energies?

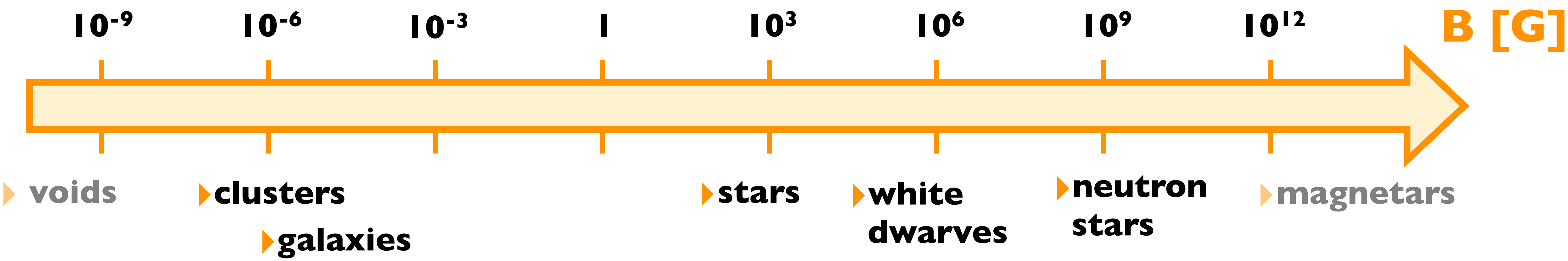
nature

- what are UHECRs made of?

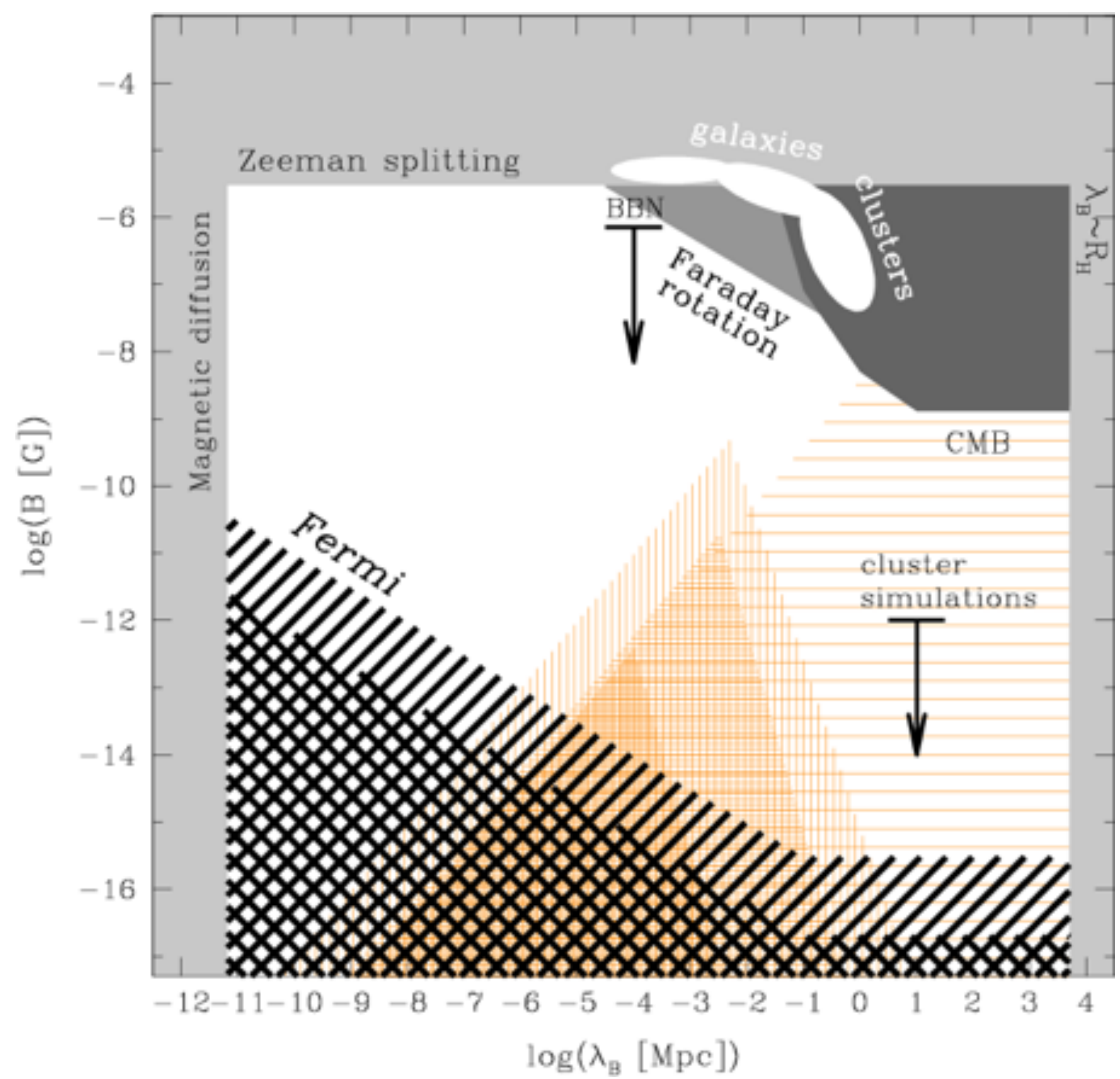
can we do UHECR astronomy?

- observables from CR experiments: spectrum, composition, anisotropy
- magnetic field determine the trajectory of particles
- magnetic fields and matter distribution may be correlated
- to do UHECR astronomy we need to understand magnetic fields (galactic and extragalactic)
- signatures of magnetic fields and matter distribution may be imprinted in experimental data

cosmic magnetic fields

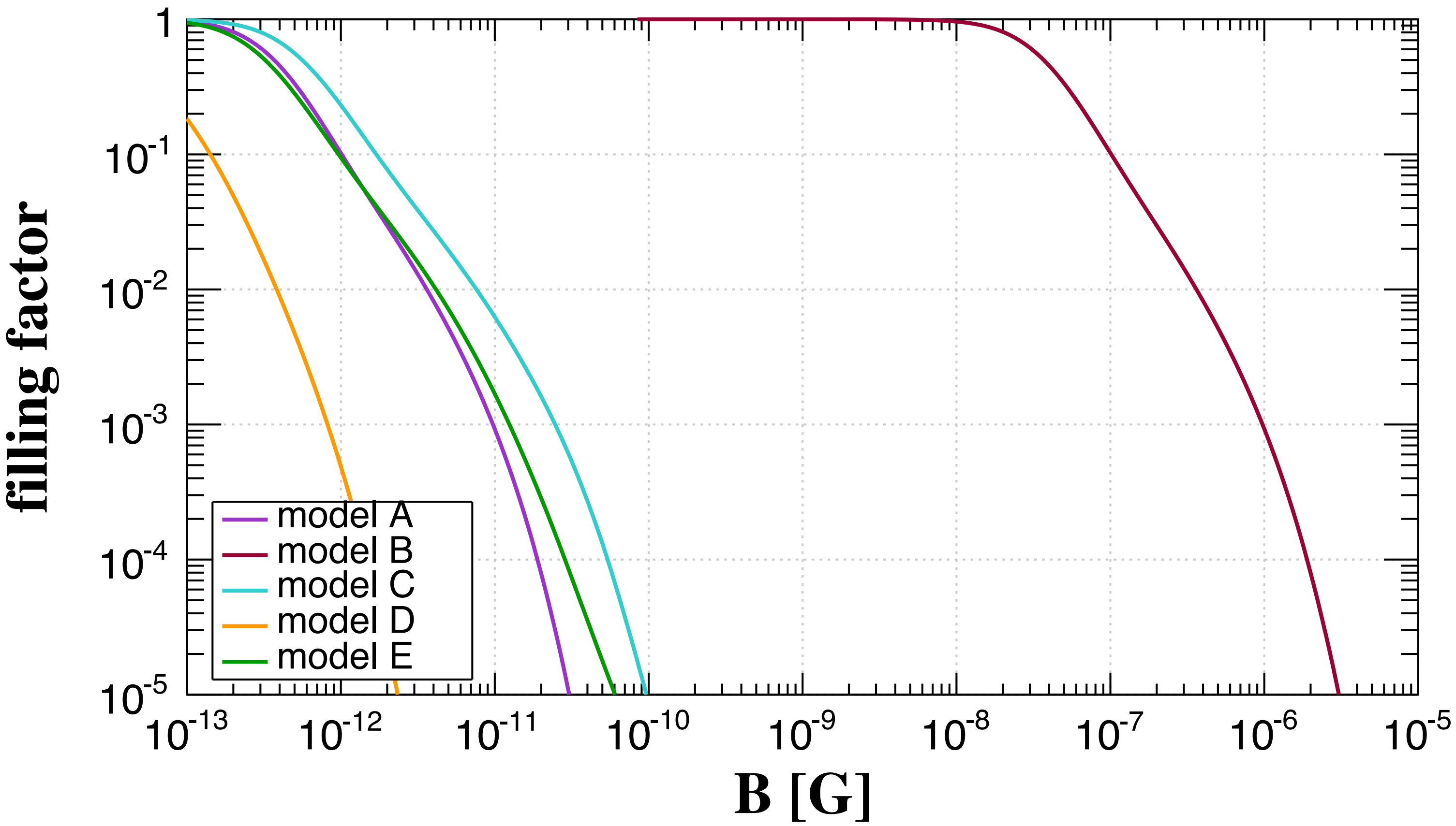


- are there cosmological magnetic fields?
- how were the magnetic fields in the universe created?
  - astrophysical (Biermann battery)
  - cosmological (inflation, phase transitions)
- lower limits: electromagnetic cascades
- upper limits: Zeeman splitting



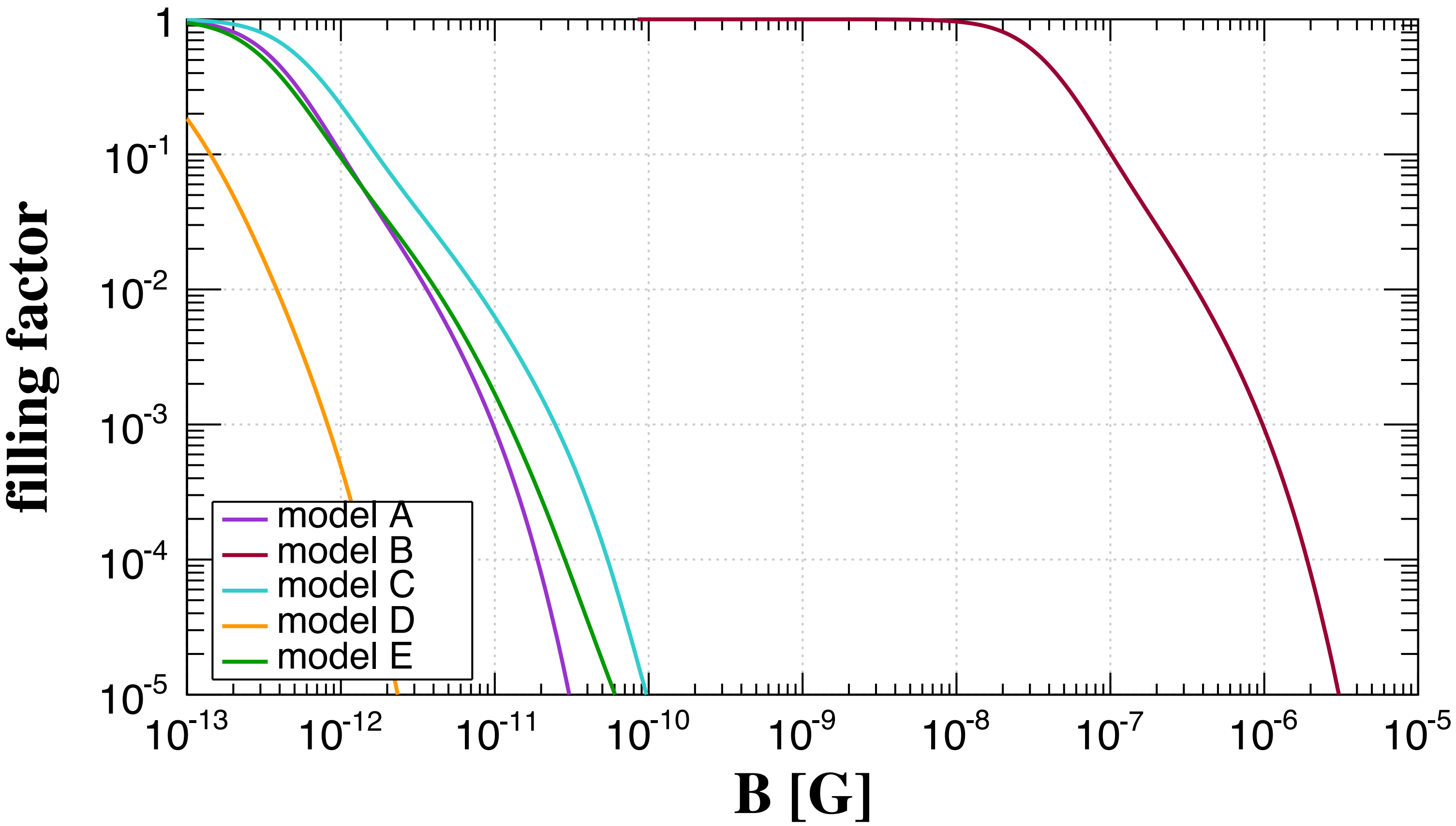
Neronov, Vovk. Science 328 (2010) 73

the MHD simulations



- **model A**: 256^3, fiducial-like
- **model B**: 256^3, initial B seed 10^5 times stronger
- **model C**: 256^3, power in small and large k range
- **model D**: 256^3, power in small k range
- **model E**: 512^3, fiducial-like

- 200 Mpc/h box
- simulations being done by M.-S. Shin, J. Devriendt, ...
- adaptative mesh refinement (AMR) using the RAMSES code [Teyssier '02]
- 10 levels of refinement
- comparison of models A and B → can we rescale the magnetic field? YES
- comparison of models A and E → convergence for higher resolution? MORE OR LESS
- models C and D → does the initial seed field affect UHECR deflection? A LOT



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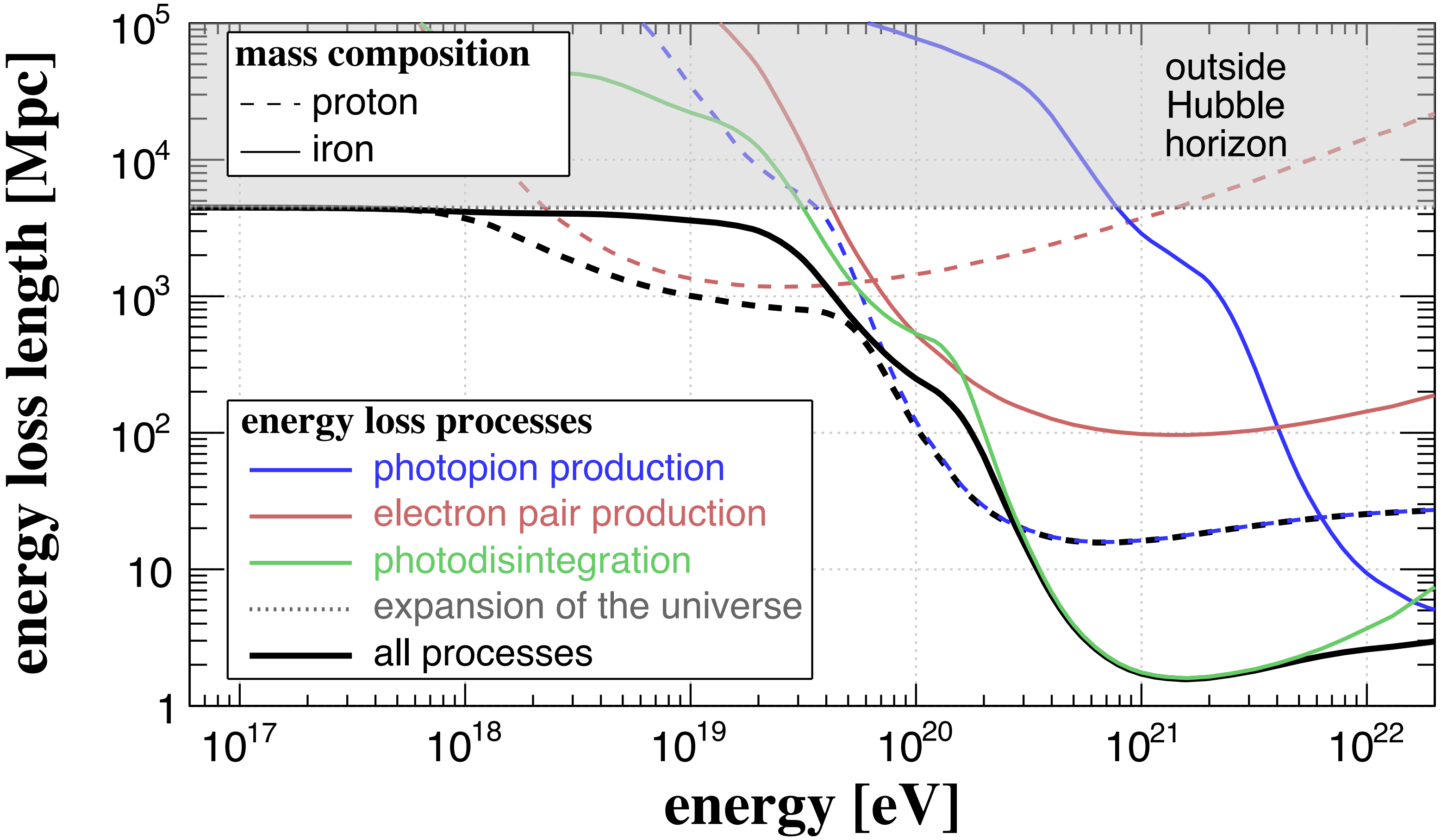
UHECR propagation

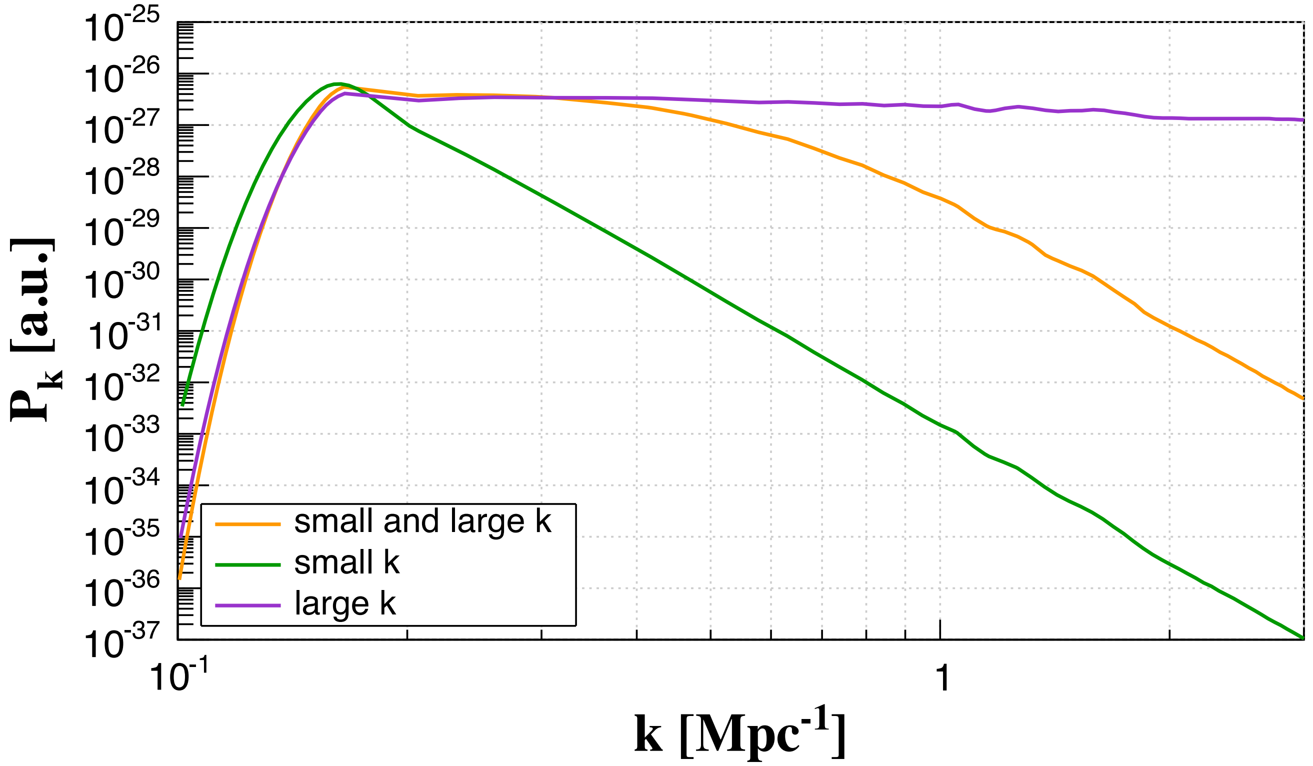
CRPropa

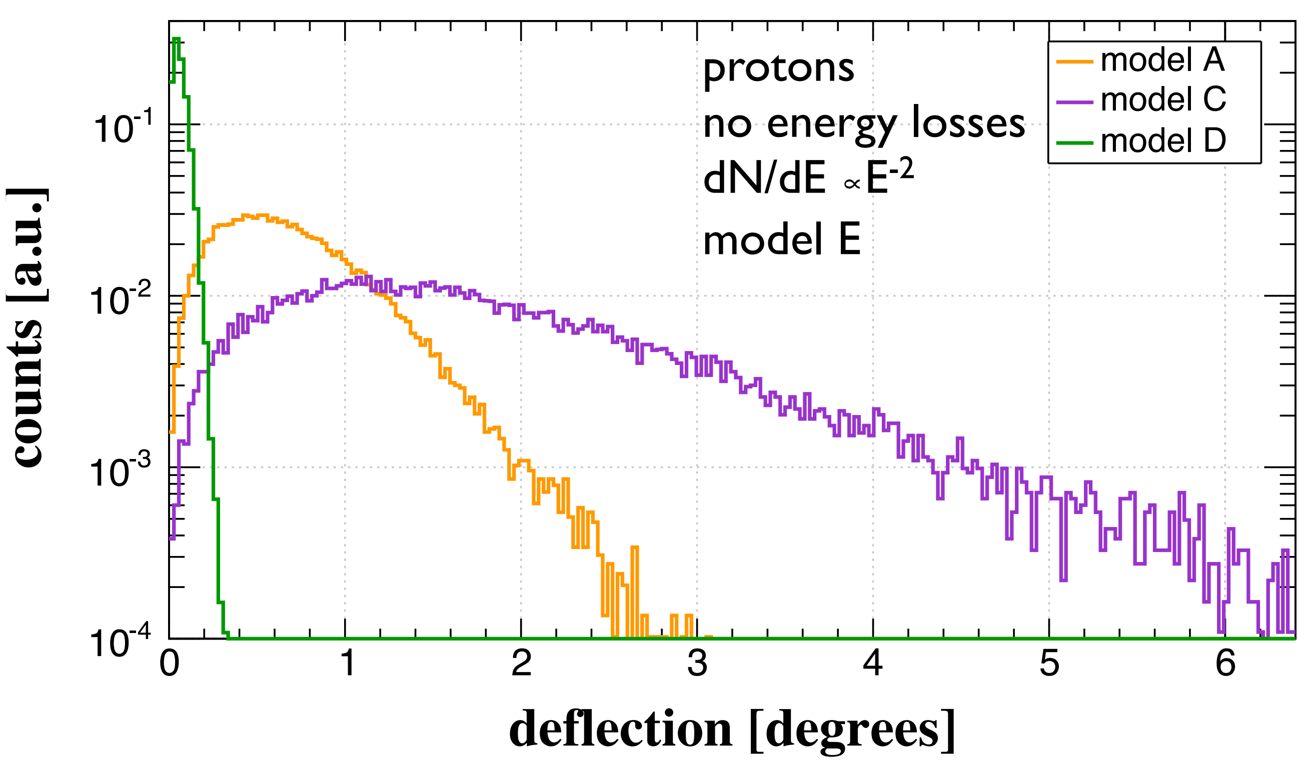
- CRPropa [Armengaud+ ’07]: propagation of cosmic ray protons and secondary γ and υ
- CRPropa 2 [Kampert+ ’13]: extended for nuclei; official release
- CRPropa 3 [RAB *et al.* arXiv:1307.2643]: development version; complete redesign of the code, cosmology in 3D, galactic magnetic field, Monte Carlo UHE photon, ...
- available in crpropa.desy.de



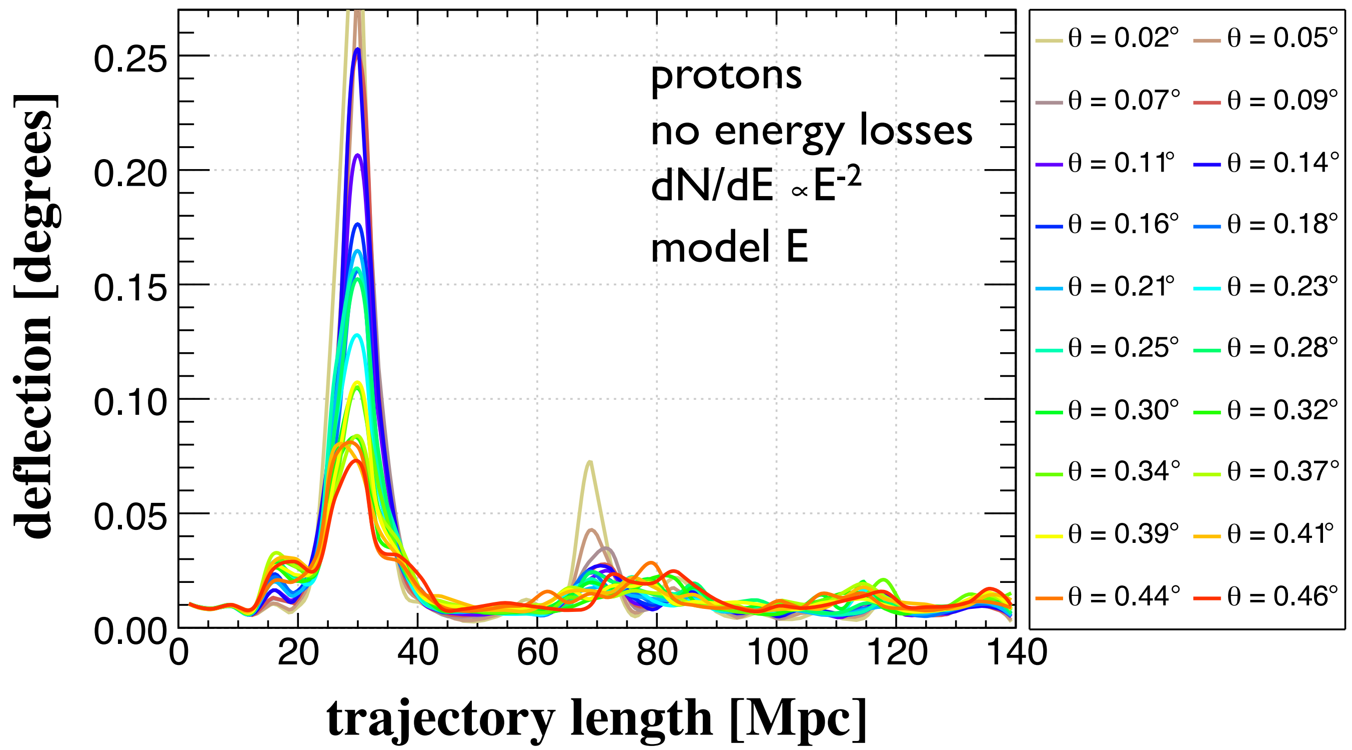
- 3D simulations with relevant energy losses due to the interaction with CMB and IRB
- detailed treatment of nuclear interactions
- for fast readout of the AMR grid, an interface between CRPropa and the grid was developed, based on SQLite

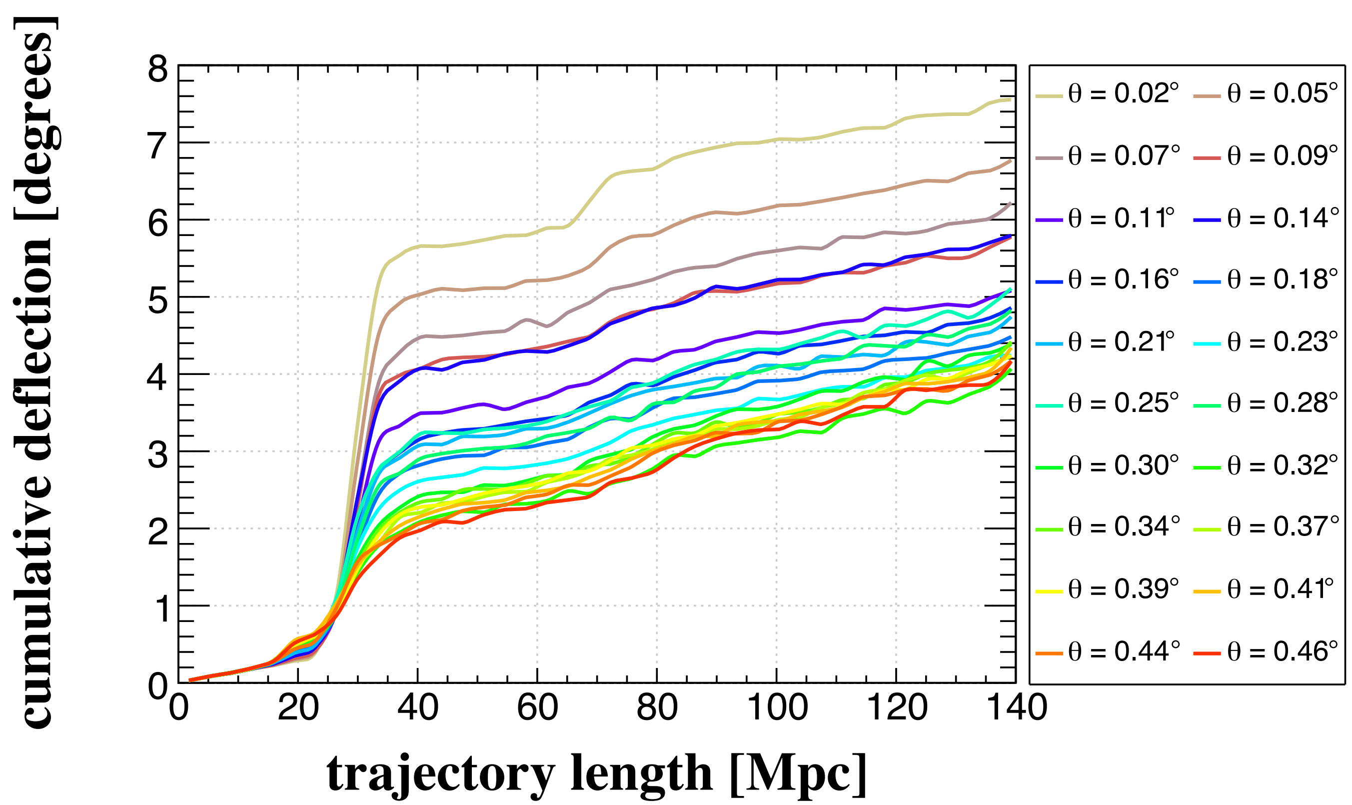
effects of B seed





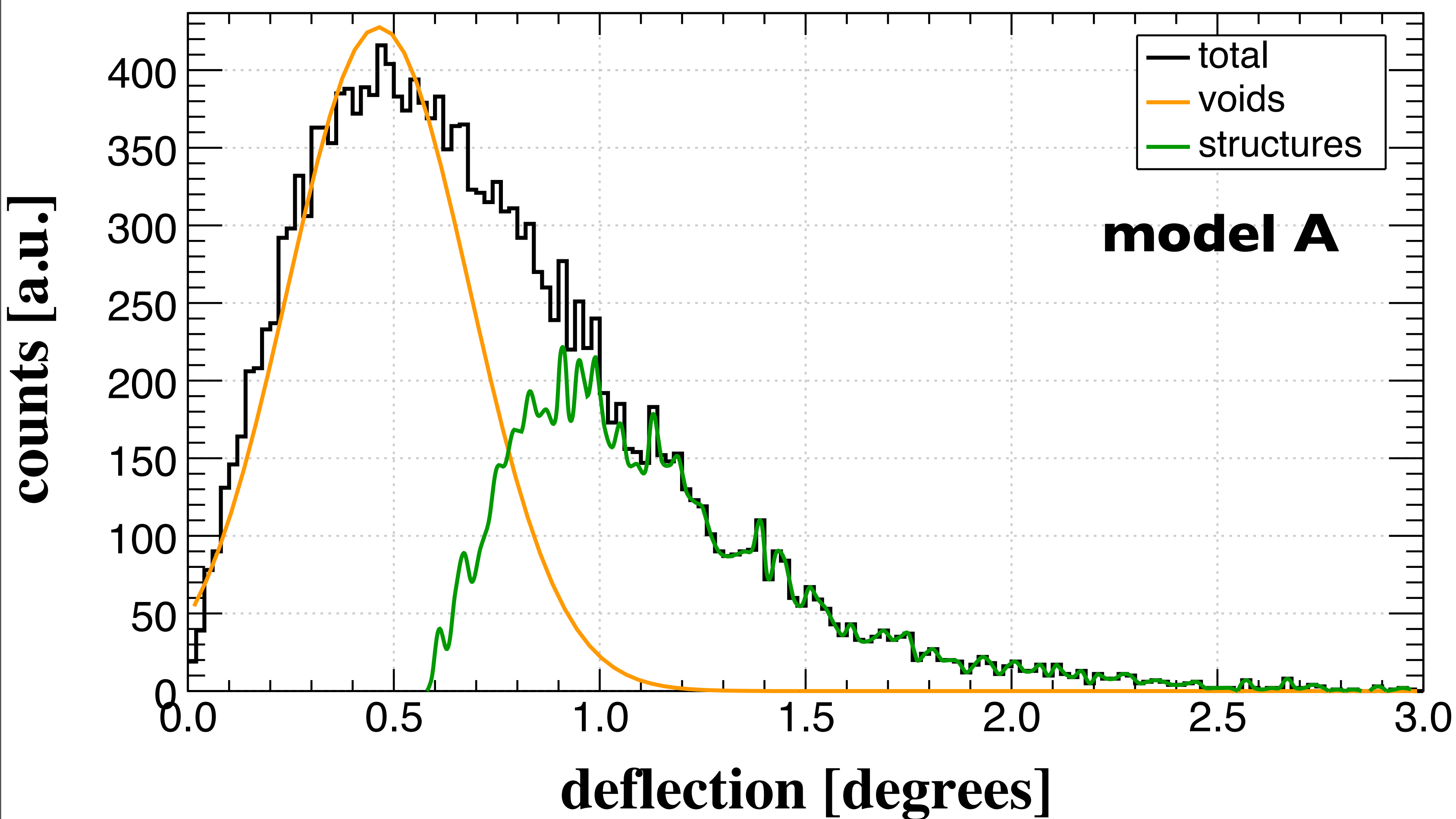
UHECR tomography





- simulation of events recording its full trajectory, changing its initial angle within a cone of θ
- the average over 100 realization for each angle is plotted
- high deflections observed when particles cross structures
- useful for cross checks
- size of the structure is given by the angle of the cone in which the deflections start to become small, and the size (trajectory length) around peaks

isolating the effect of structures

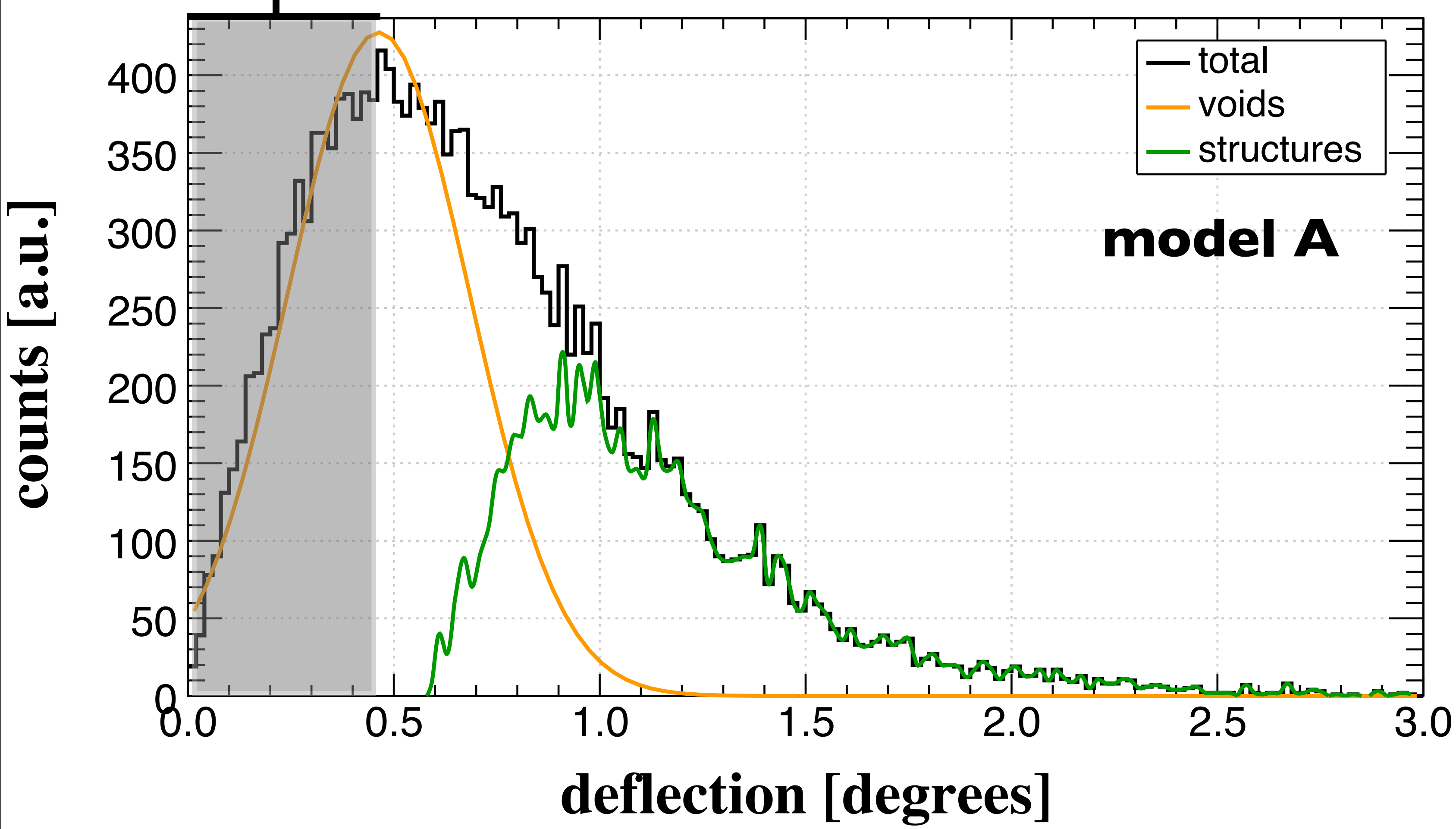


protons
no energy losses
dN/dE $\propto E^{-2}$
model E

isolating the effect of structures

fitting deflection in the voids with gaussian (assuming the magnetic field in the voids has gaussian distribution)

the gaussian is fitted up to the maximum of the distribution of deflection (left of the maximum), since most of the volume is dominated by voids



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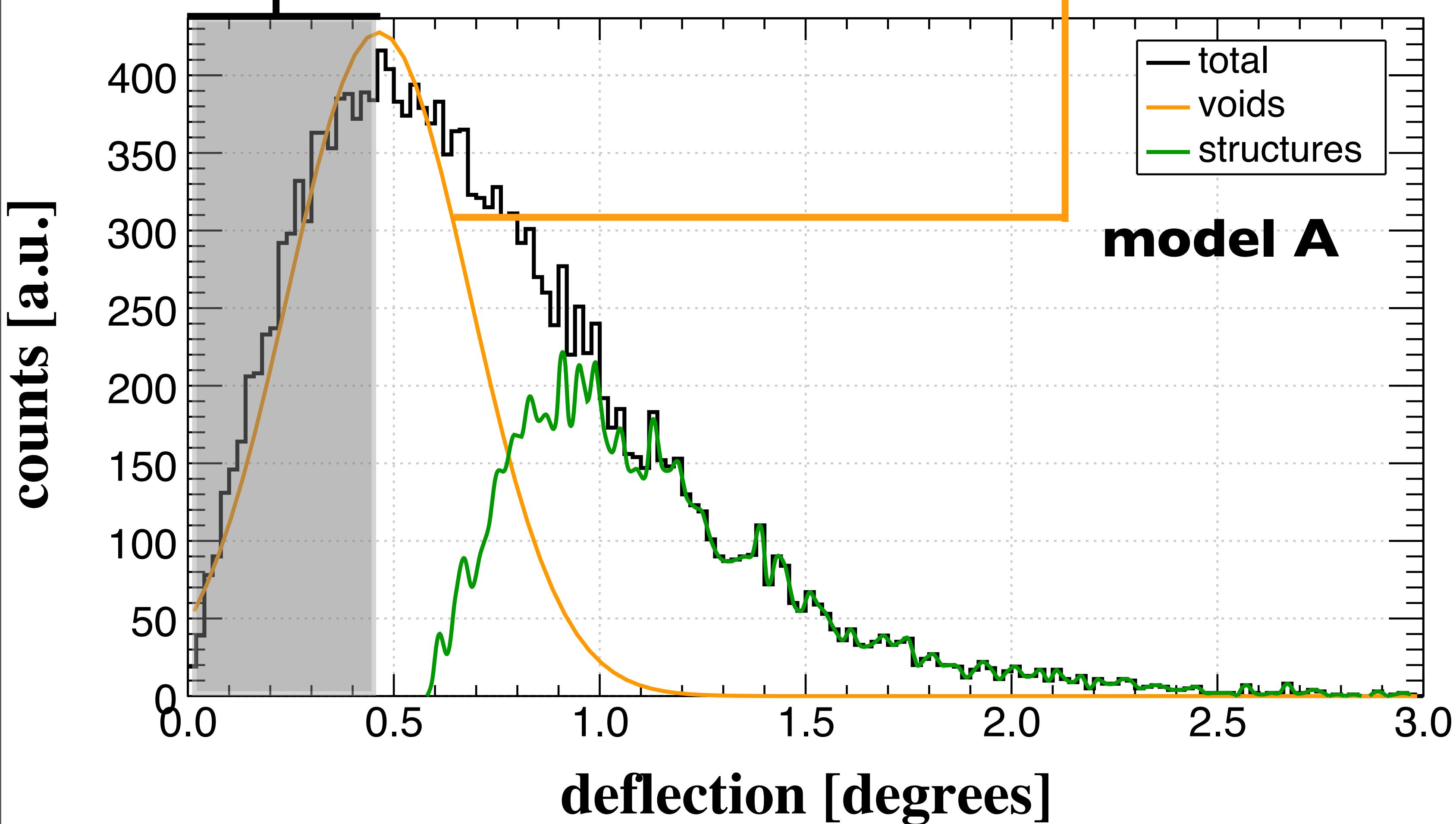
the parameters from the fit are used to build a gaussian for the whole range of deflections (orange curve)



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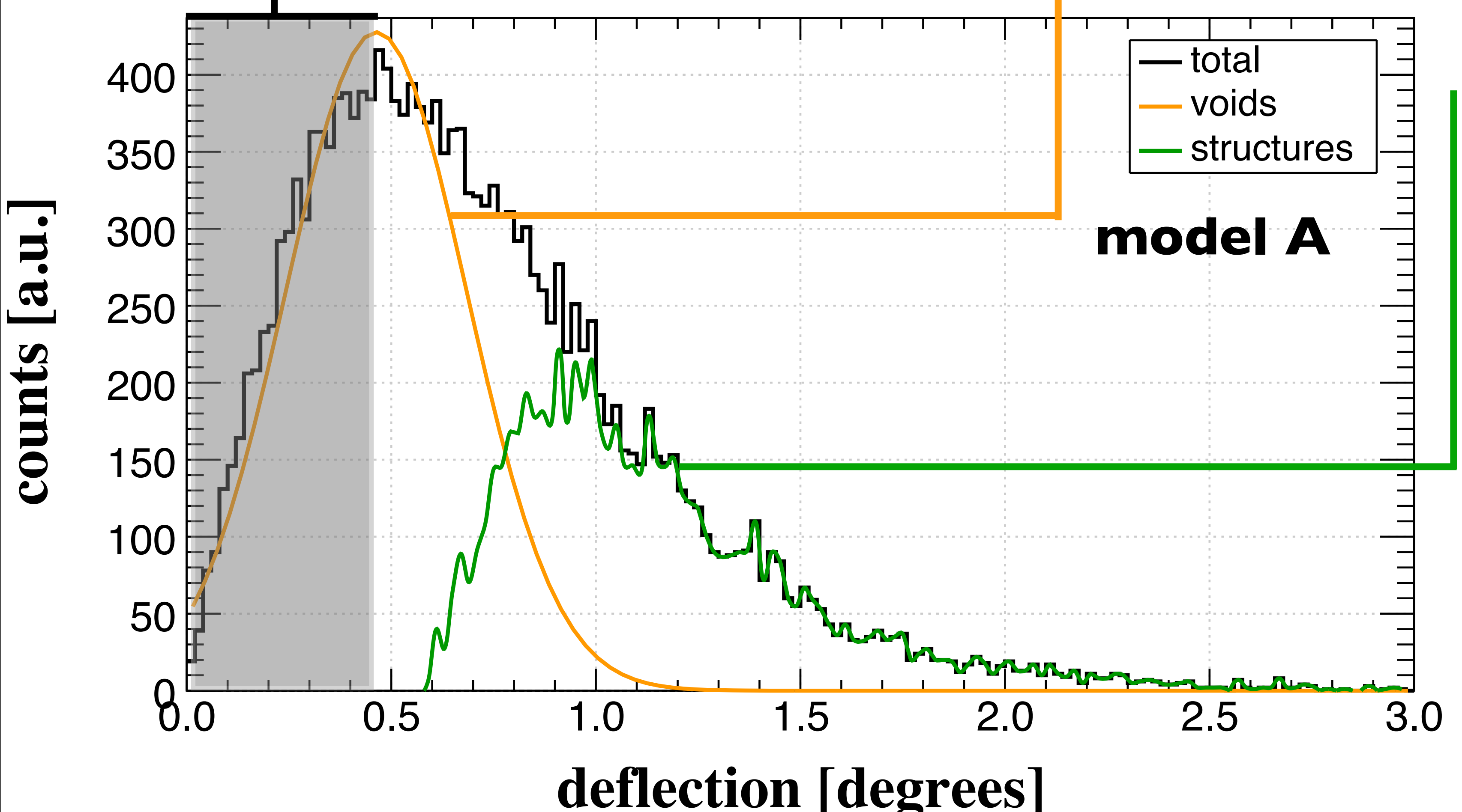

we subtract the effects of the voids (orange curve) from the total distribution (black curve) → deflection due to structures (green curve)

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no energy losses
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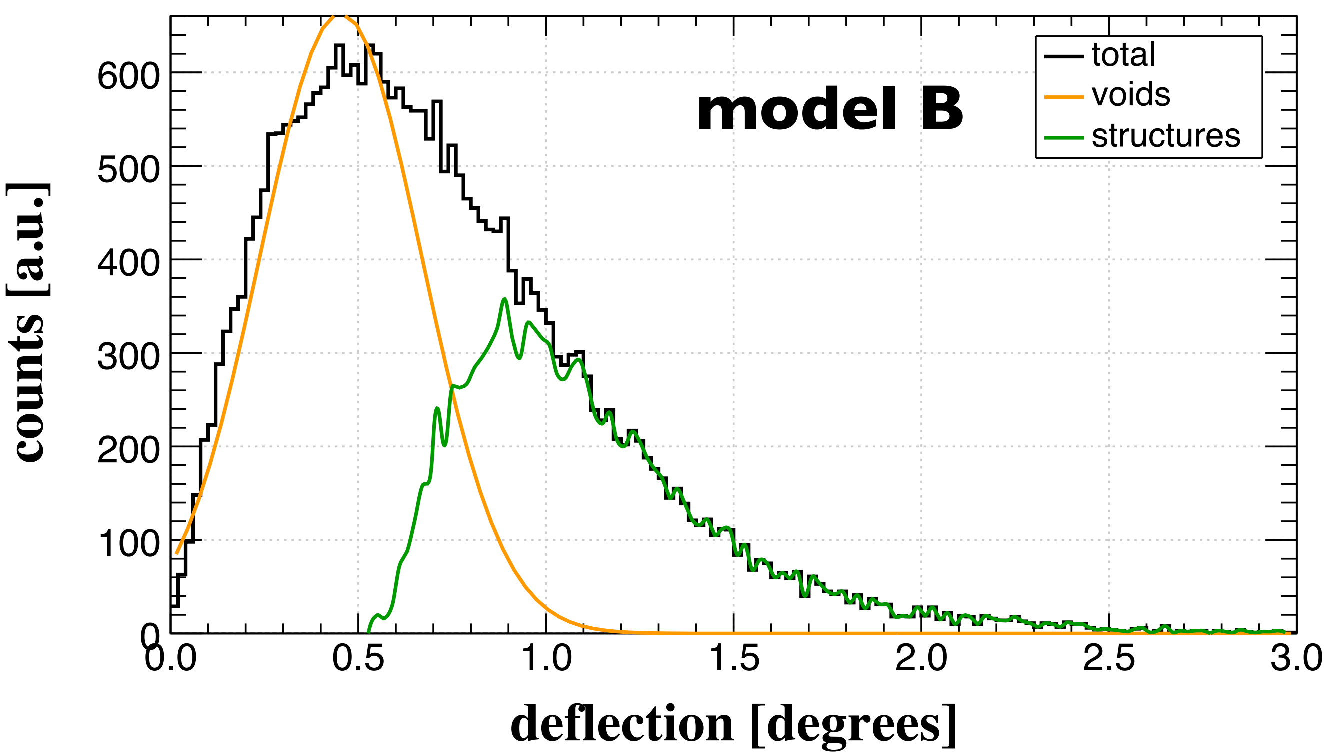
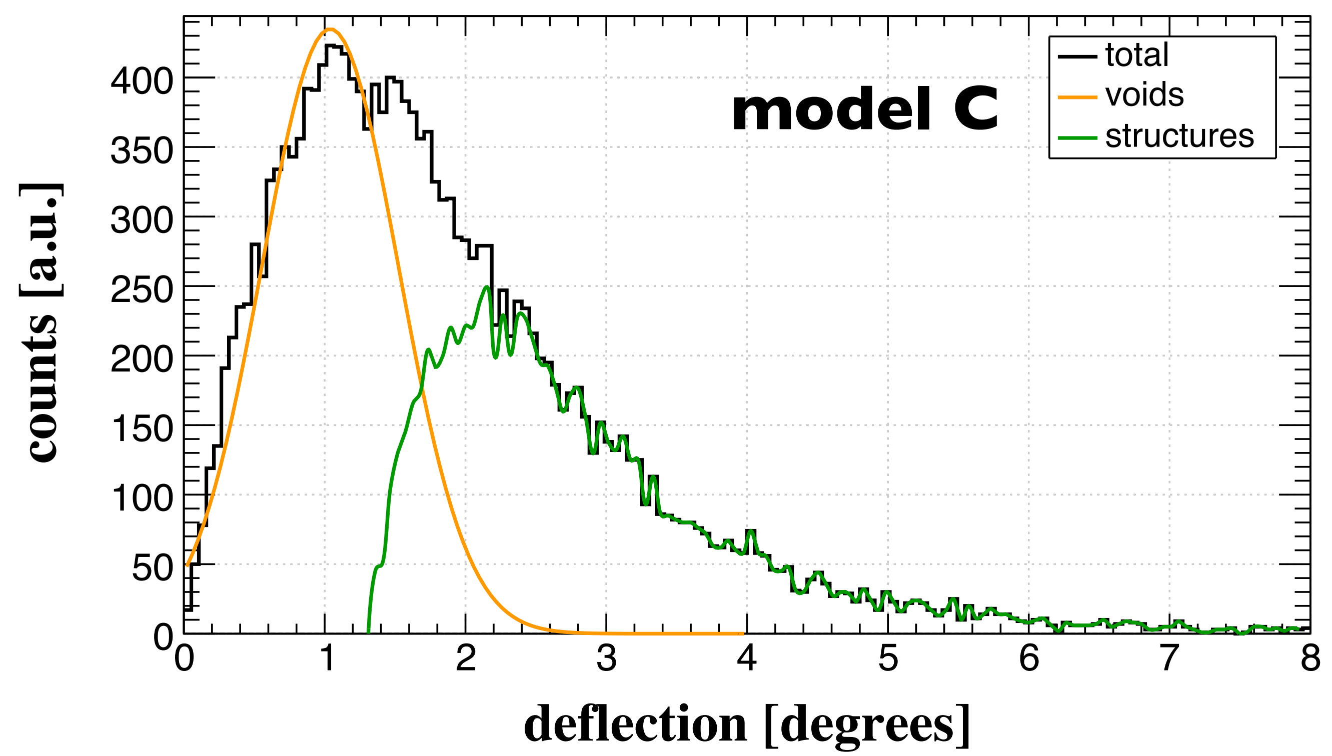
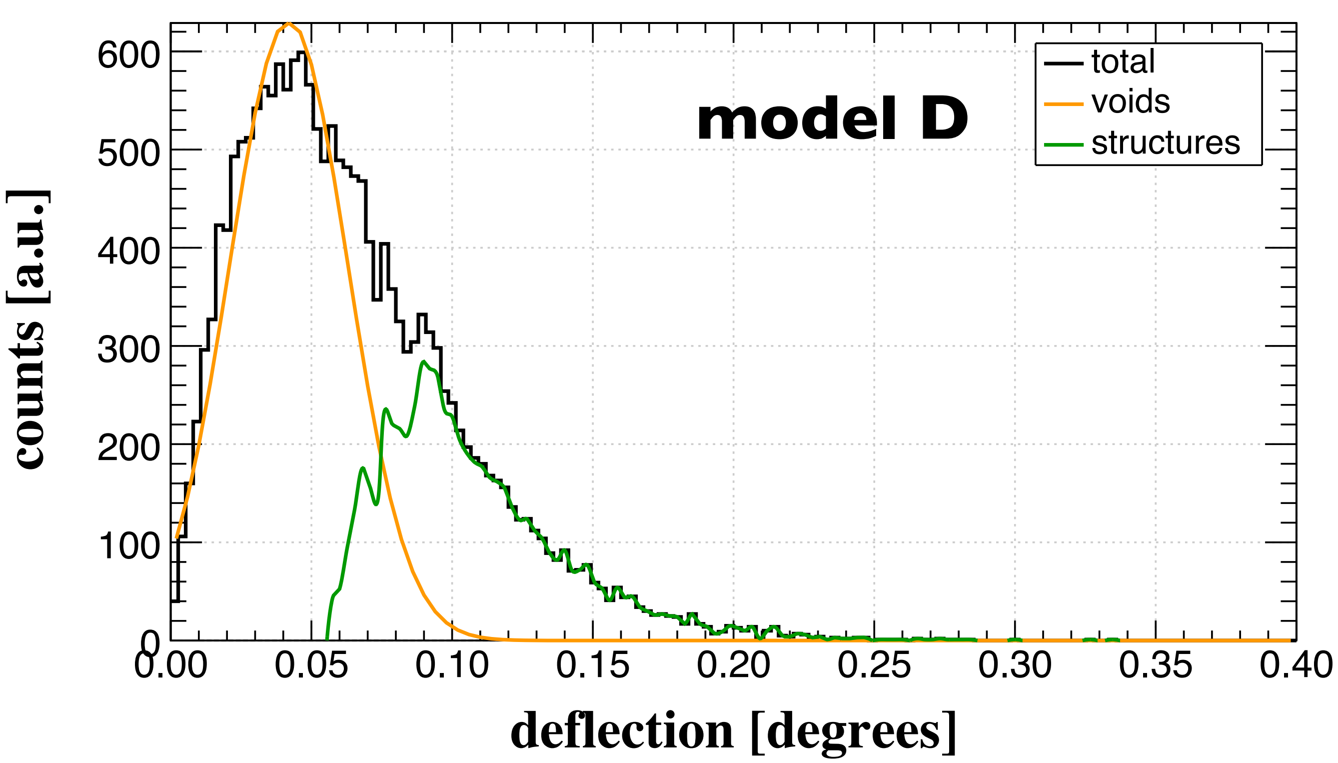
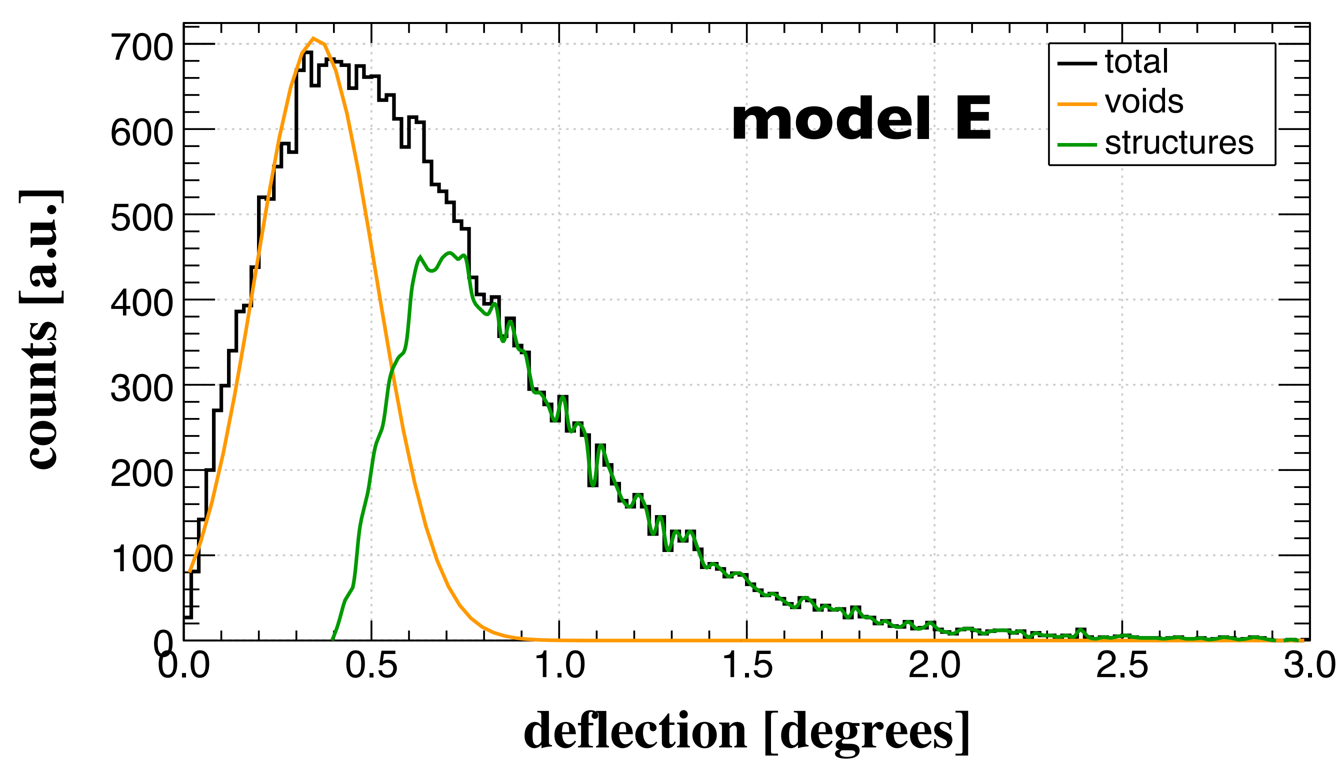
model E

isolating the effects of structures

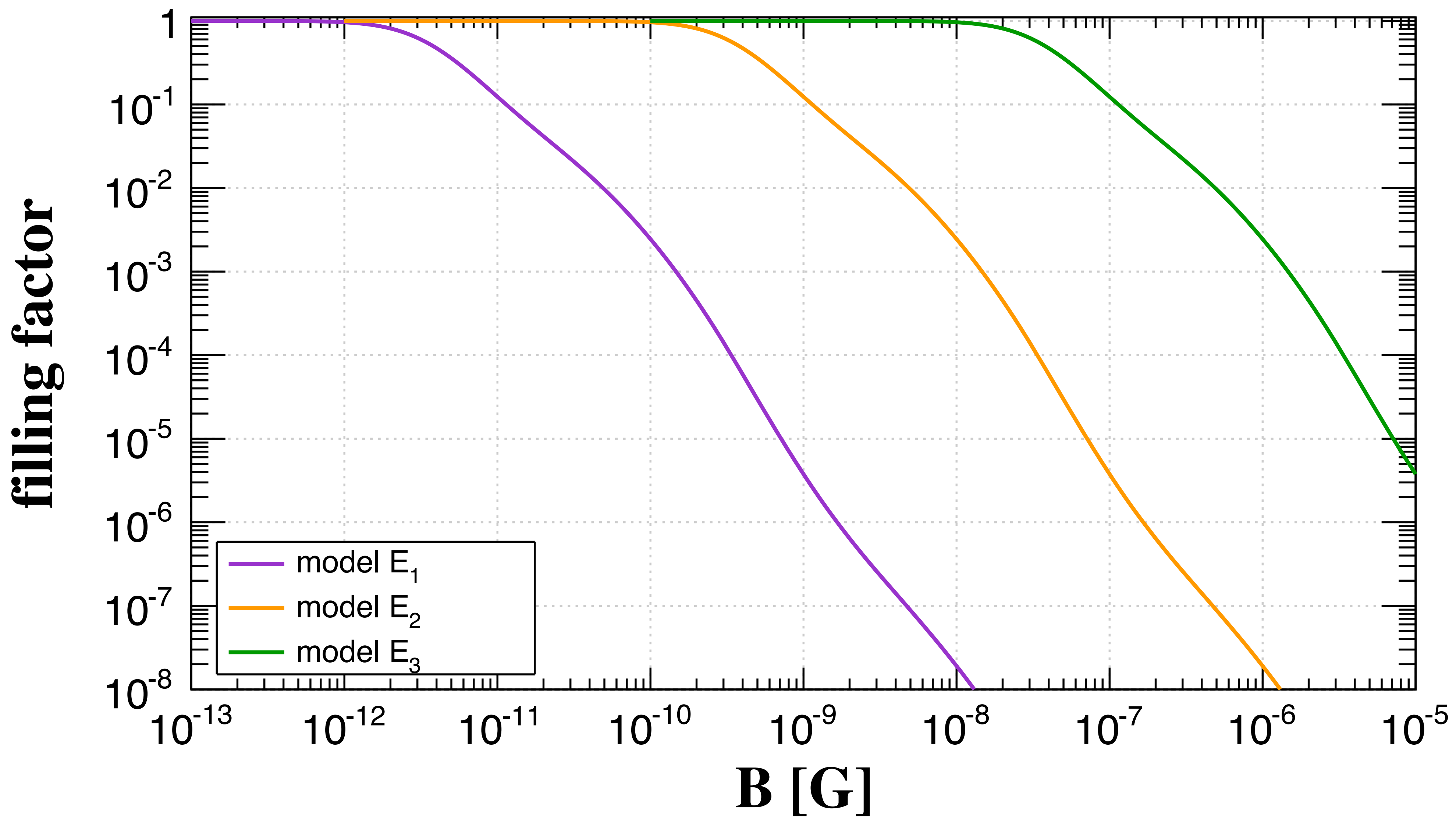






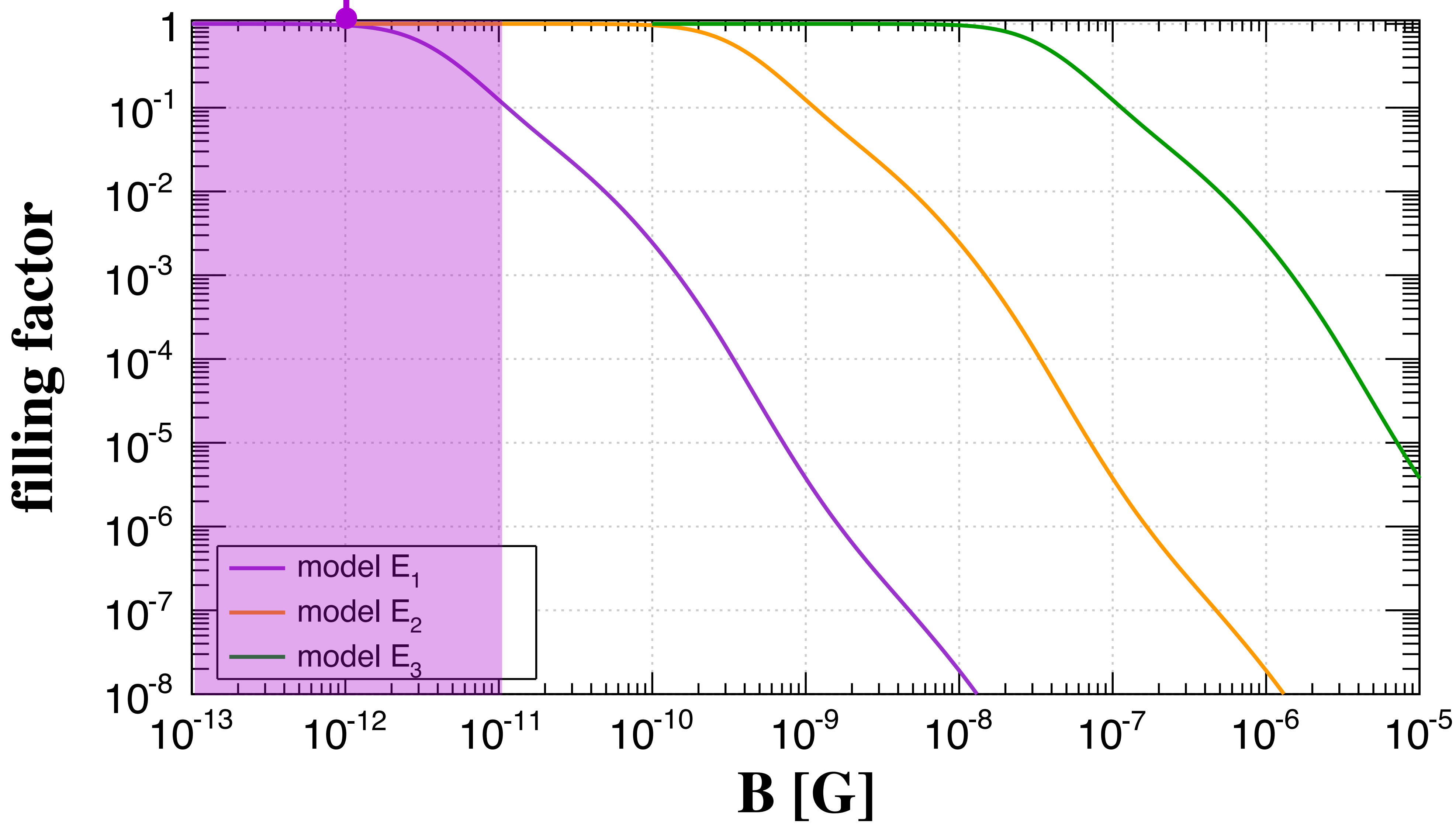


models E_i: filling factors



models E_i: filling factors

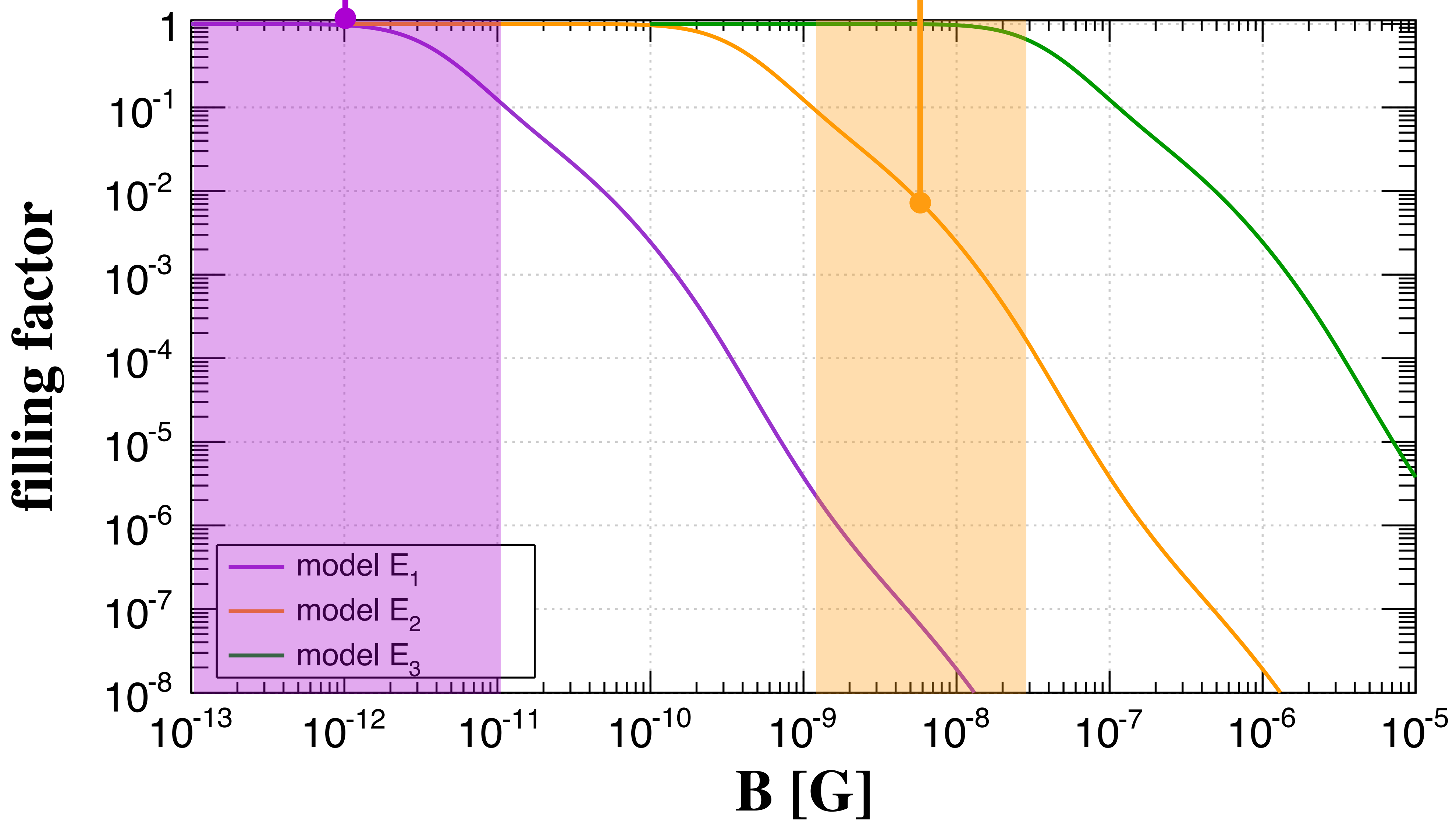
minimum model: normalized to lower limits in voids



models E_i: filling factors

minimum model: normalized to lower limits in voids

archetype model: self consistent normalization from baryon density

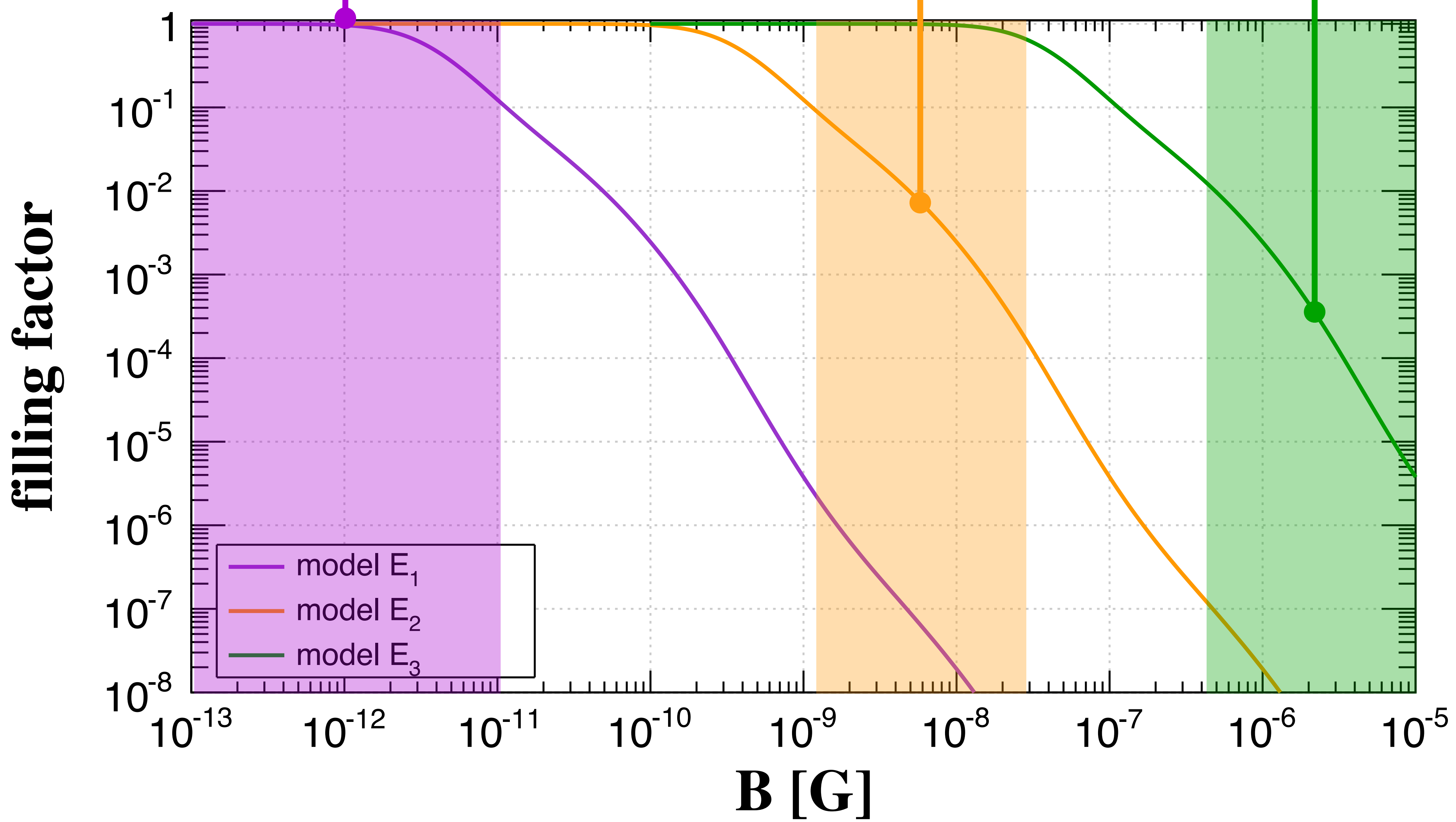


models E_i: filling factors

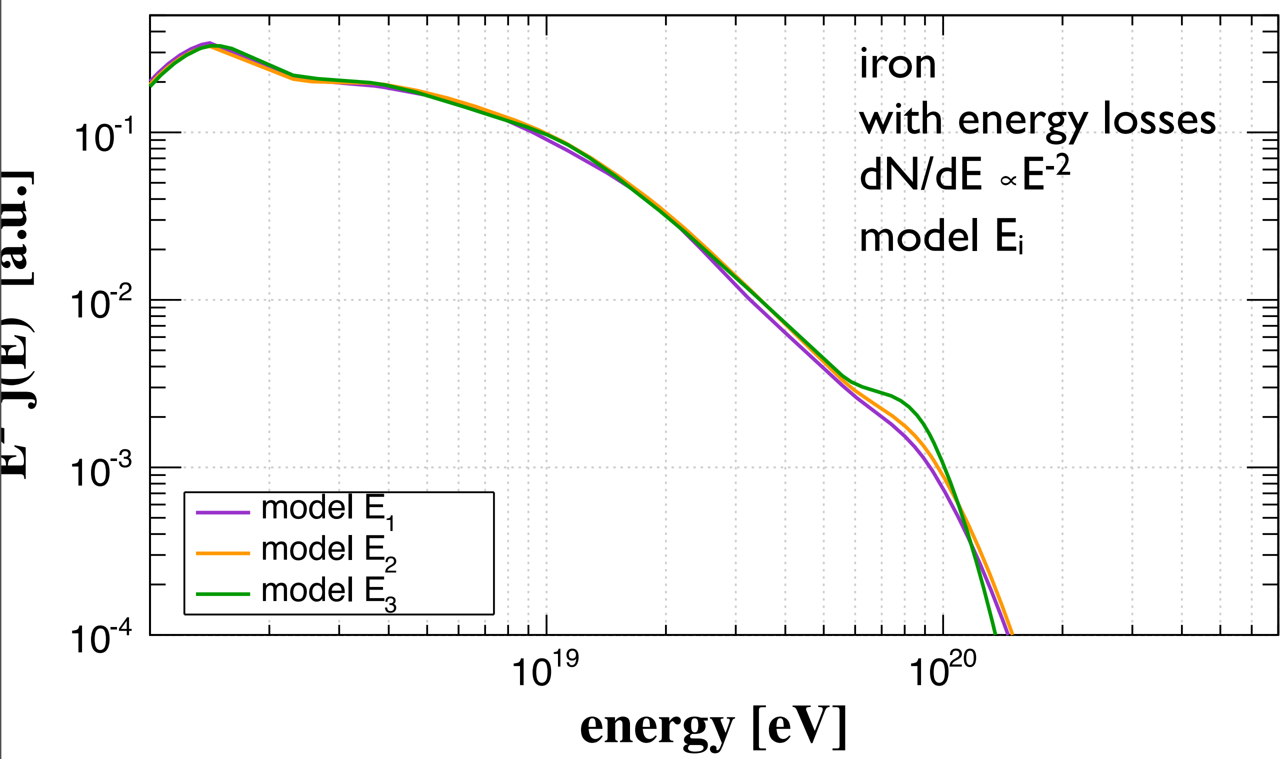
minimum model: normalized to lower limits in voids

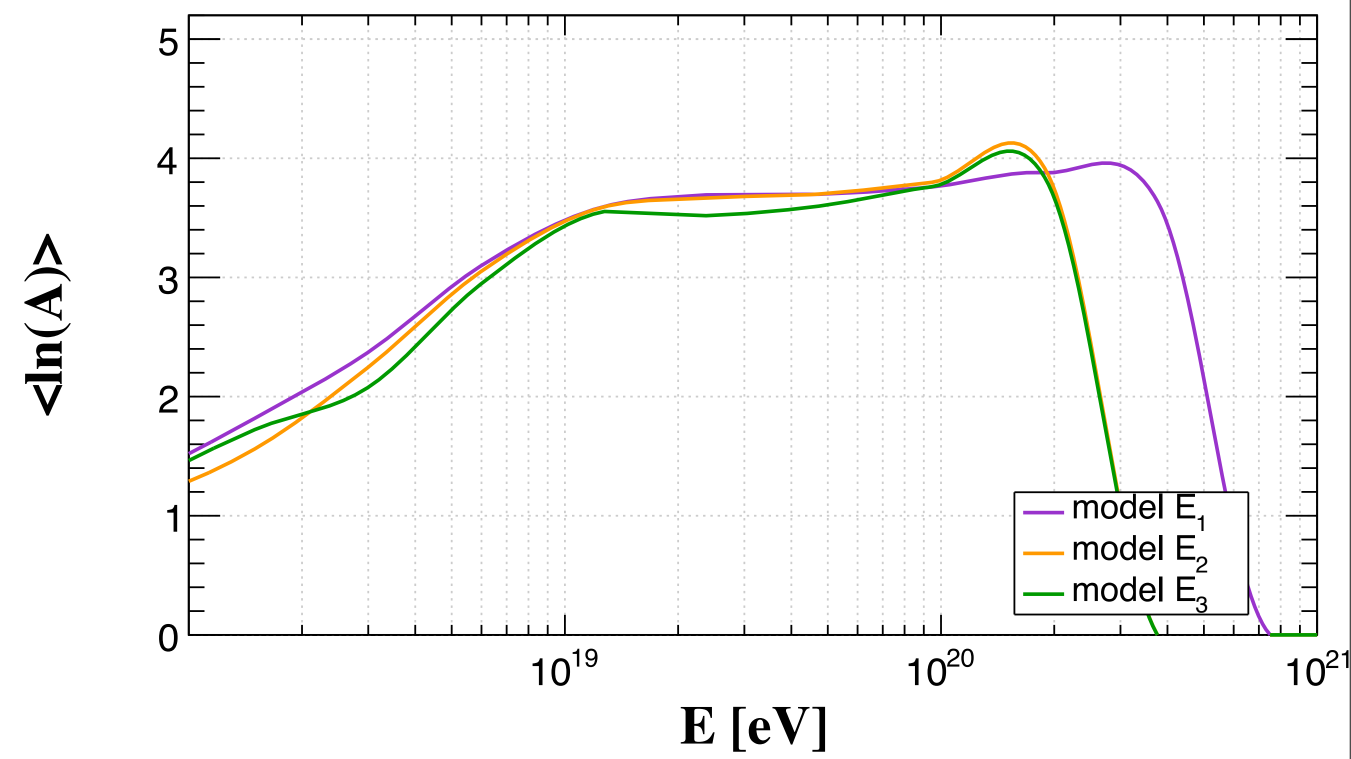
archetype model: self consistent normalization from baryon density

maximum model: normalized to clusters of galaxies

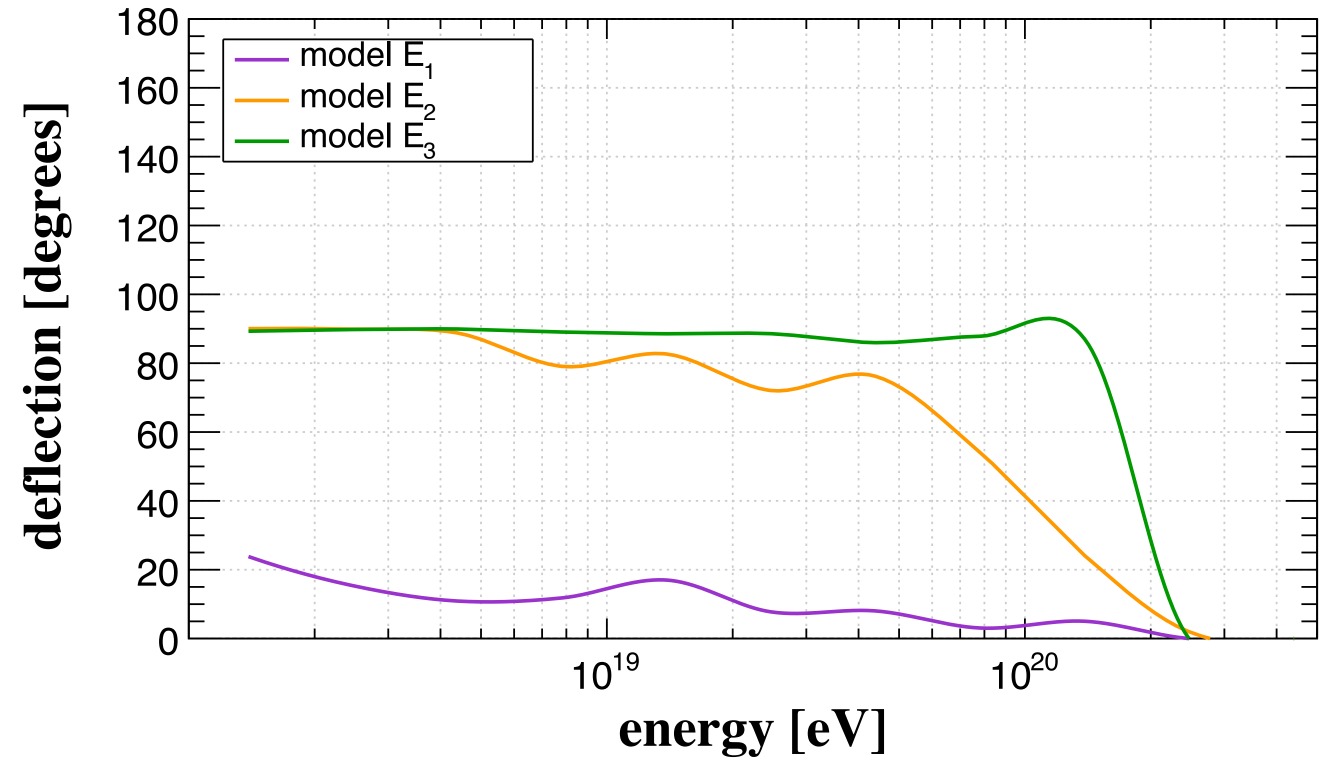


models E_i: spectrum and compostion



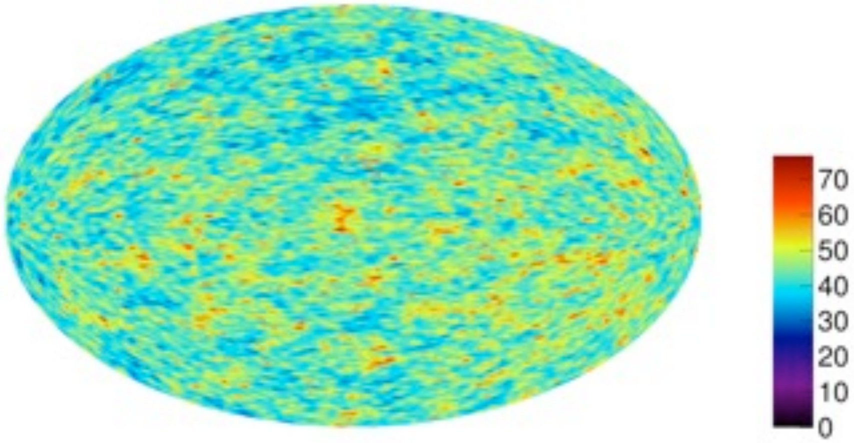


- this is not a realistic scenario (in terms of composition); it is a test in of the effects of different magnetic field normalizations
- in this particular case the magnetic field normalization has a small effect on the spectrum
- the composition is significantly altered
- the deflections are obviously dependent on the way B is normalized

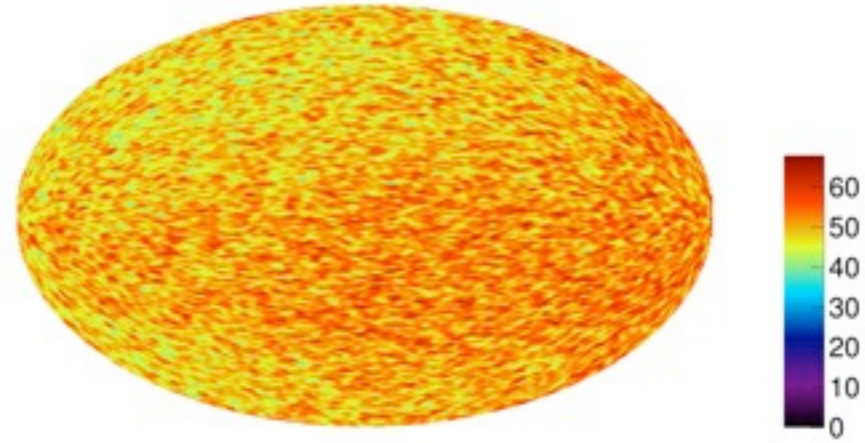


models E_i: anisotropies

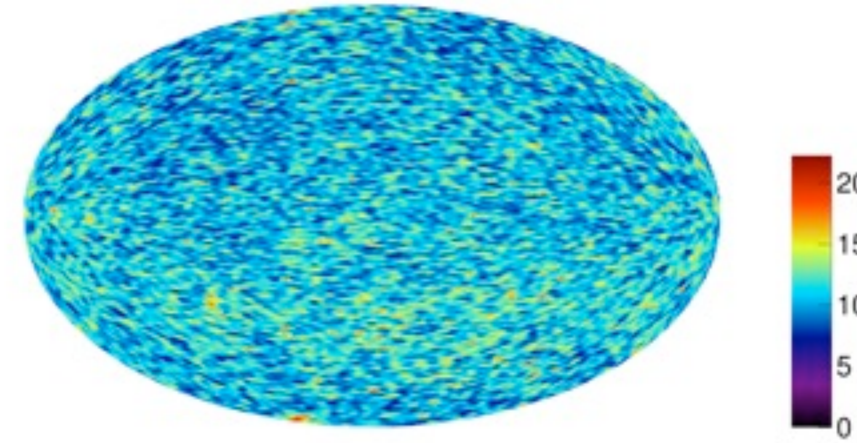
model E_1 (EG)



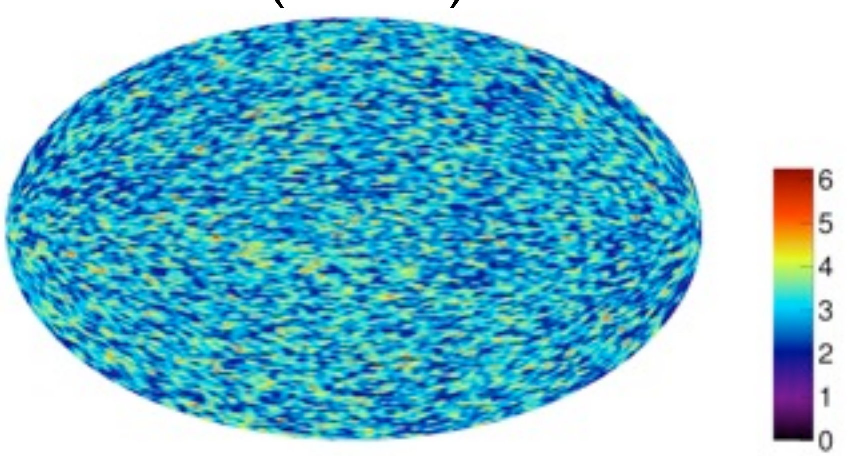
model E_2 (EG)



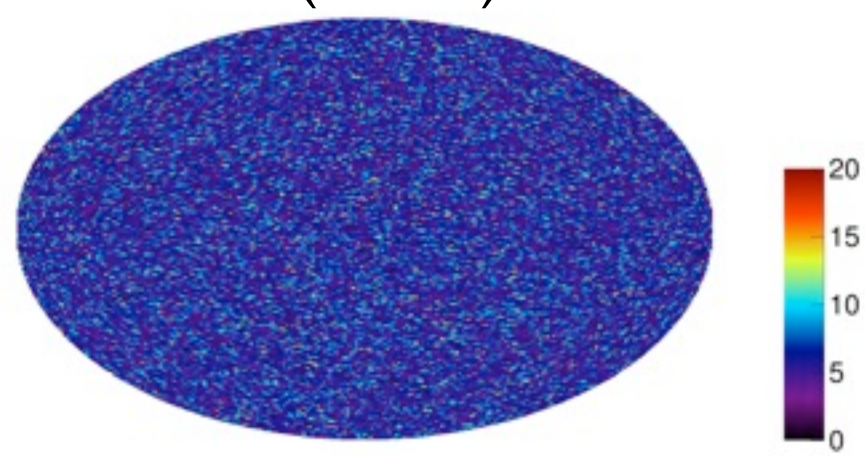
model E_3 (EG)



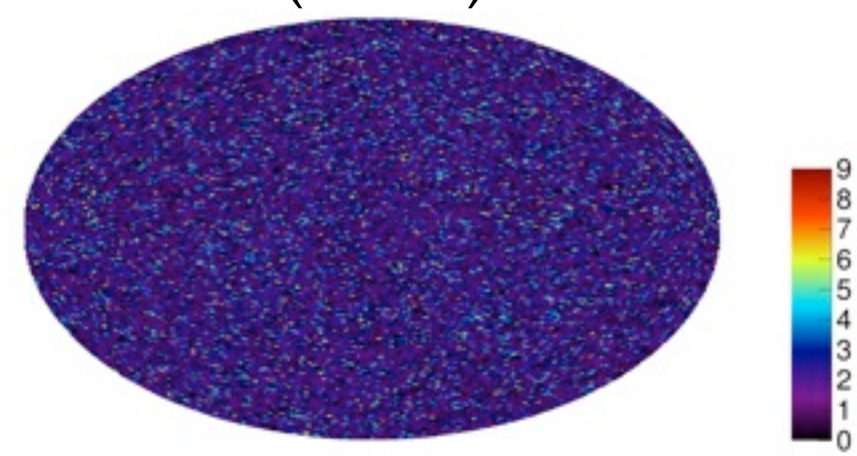
model E_1 (EG+G)



model E_2 (EG+G)



model E_3 (EG+G)



	extragalactic only	extragalactic + galactic
model E_1	0.09	0.02
model E_2	0.09	0.01
model E_3	0.08	0.01

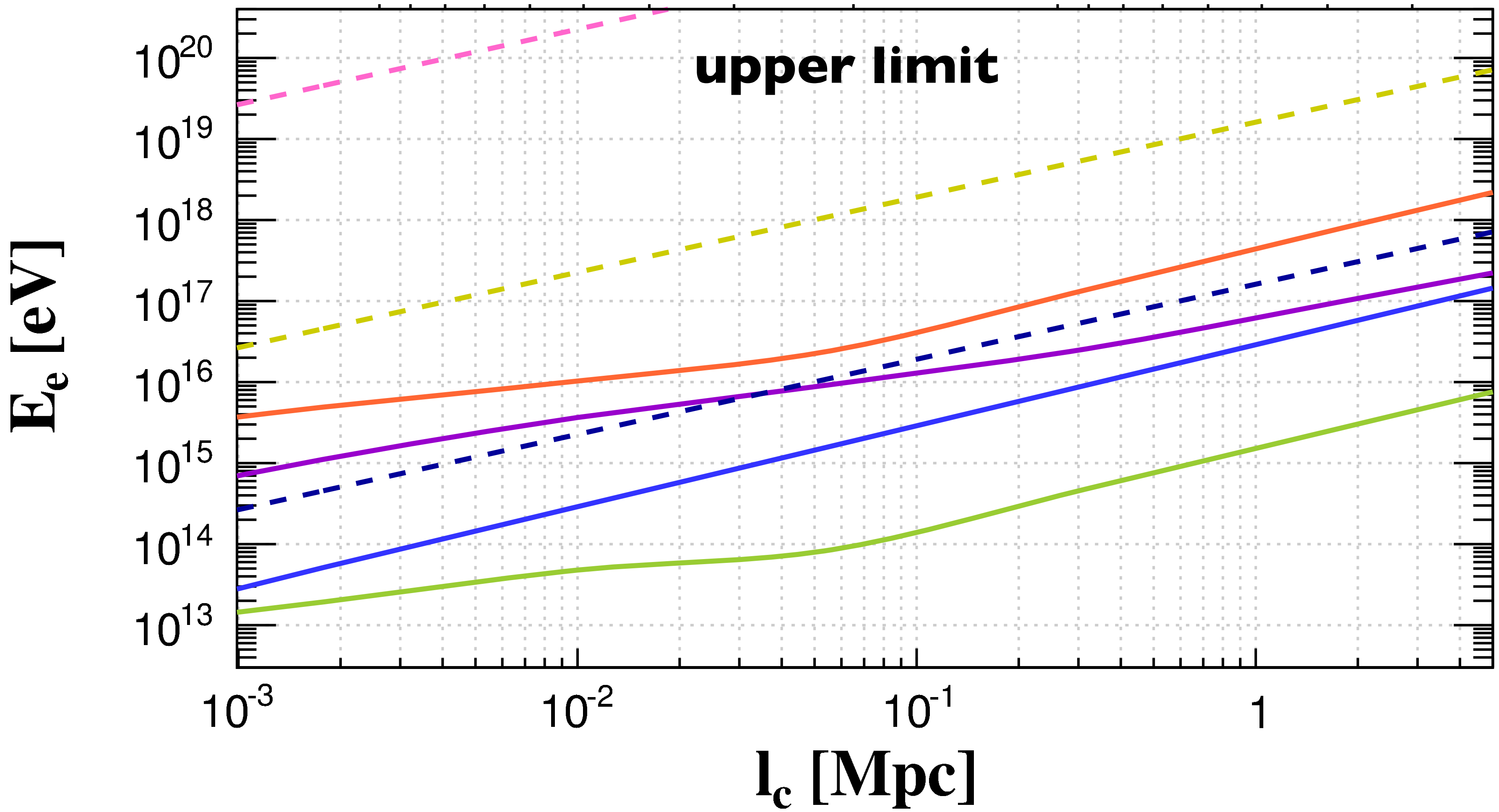
galactic magnetic field:
[Jansson & Farrar '12]

GMF lensing technique from the PARSEC code:
[Bretz+ '14]

magnetic horizons

- combined spectrum-composition fits of the Auger data suggest hard spectral indexes (γ < 2) [Taylor '13, Aloisio+ '13] → the hard spectra "problem"
- standard shock acceleration mechanism → $\gamma \approx 2$
- hard spectral indexes are compatible with acceleration by magnetars [Arons '03], young pulsars [Fang+ '12], ...
- lower energy magnetic suppression [Lemoine '05, Aloisio & Berezinsky '05]→ hard spectral indexes not needed [Mollerach & Roulet '13]
- if this suppression sets in below 10^{18} eV hard spectral indexes are still needed
- strong suppression → softer spectral indexes (compatible with Fermi acceleration)
- with realistic models of extragalactic magnetic fields → magnetic horizon effects are not relevant at EeV energies and hard spectral indexes are still required [RAB & Sigl '13]
- it is important to understand extragalactic magnetic fields, their distribution and strength

magnetic horizons

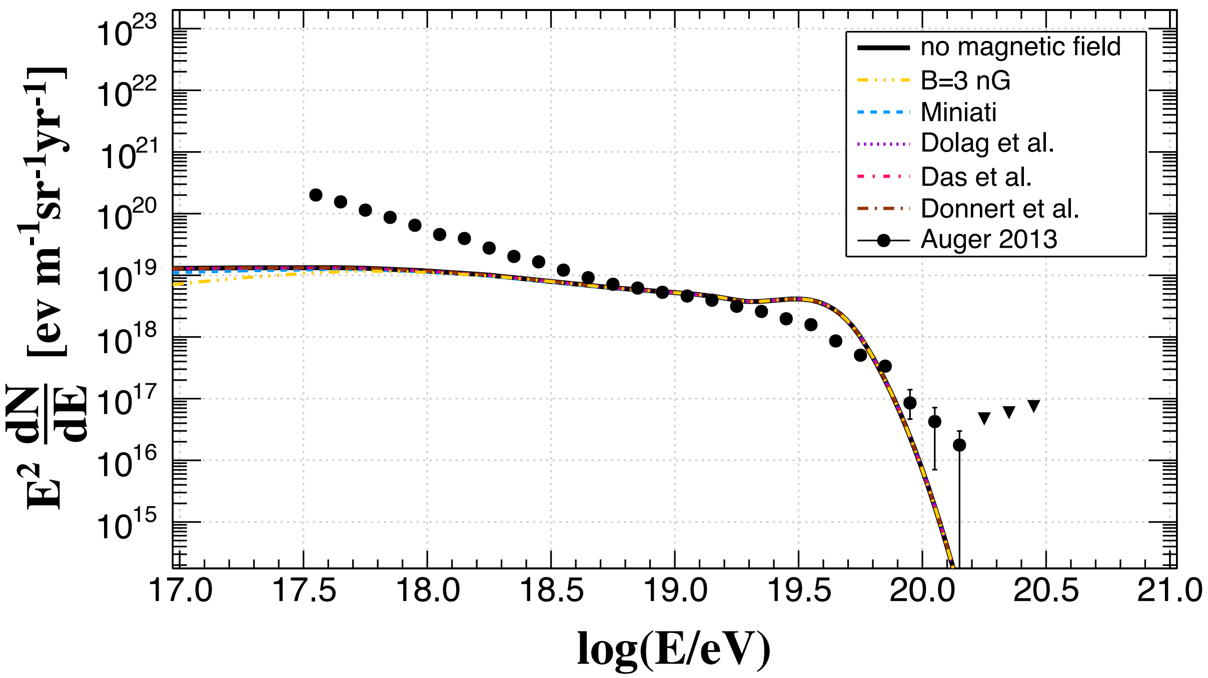


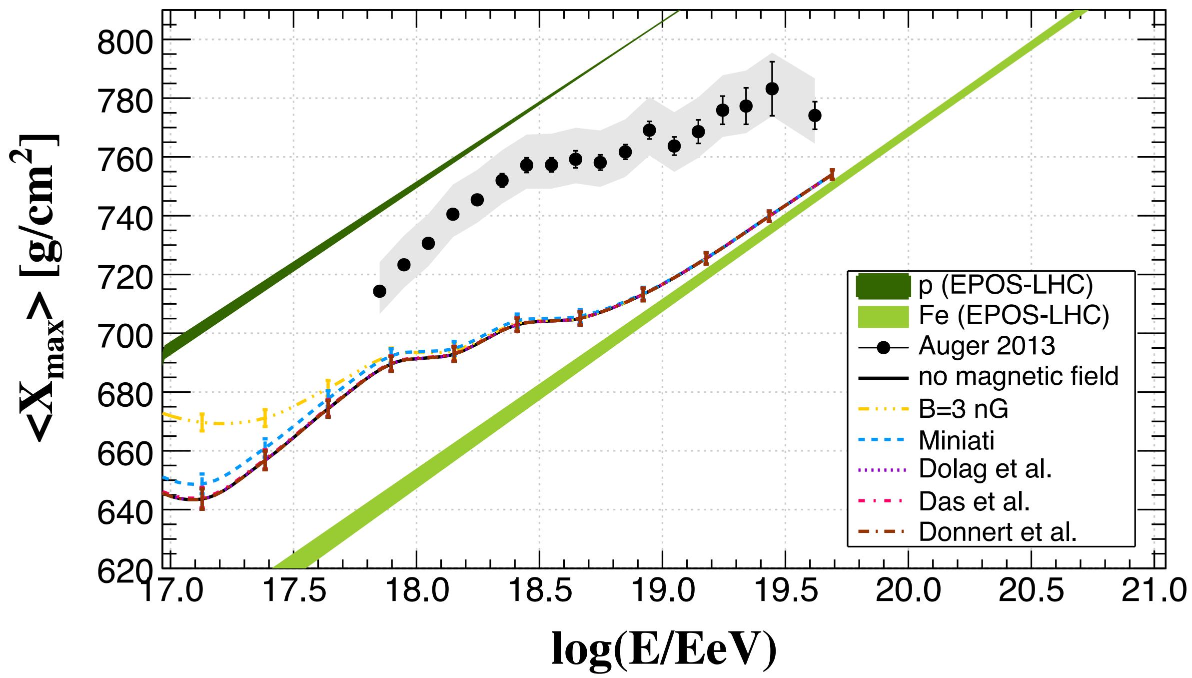
$n_s = 6\times10^{-6}$ Mpc^{-3}

$d_s \approx 13$ Mpc

Z=26

RAB & Sigl.
arXiv:1407.2643





summary & outlook

new high resolution MHD simulations

- new MHD simulations with high resolution (~1 kpc)
- different magnetic field seeds affect the propagation of CRs

normalization of the magnetic fields

- normalization of magnetic fields in cosmological simulations are important
- how to normalize: at voids, clusters or in a self-consistent way?
- spectrum and composition can be affected by these assumptions
- anisotropy patterns will also be different

magnetic horizons

- magnetic horizons are only relevant at low energies ($<10^{17}$ eV) in realistic extragalactic magnetic field models
- magnetic horizons were postulated to explain the hard spectral indexes obtained from fits of Auger data
- magnetic horizons may not solve this "problem" → UHECR sources may have hard spectral indexes

future

- working to constrain the simulations → most up-to-date extragalactic magnetic field model for UHECR propagation

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Thank you!

energy loss processes

photopion production

$$p + \gamma \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

mean free path for nuclei written as a function of the mfp for protons and neutrons

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \qquad E = \frac{E_0}{1+z}$$

ΛCDM cosmology

pair production

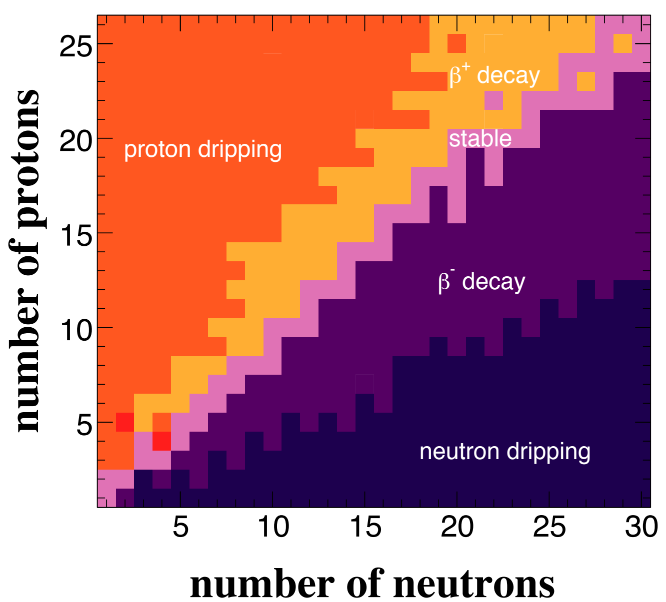
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

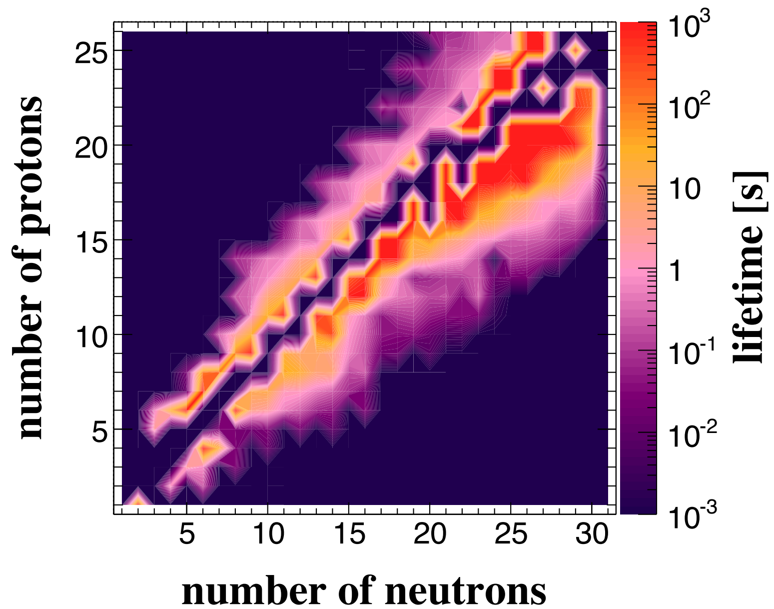
photodisintegration

$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon)d\epsilon$$

tabulated cross sections from TALYS 1.6

nuclear decay

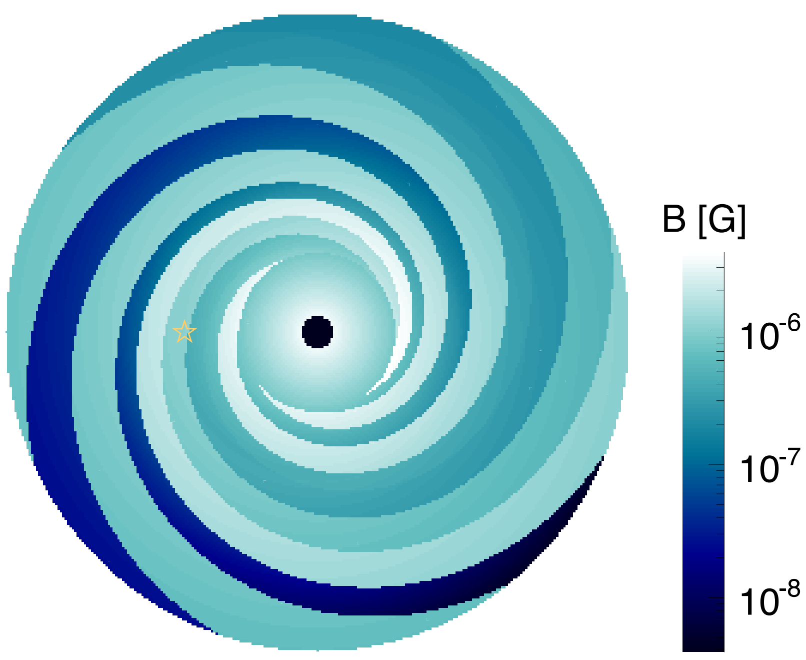




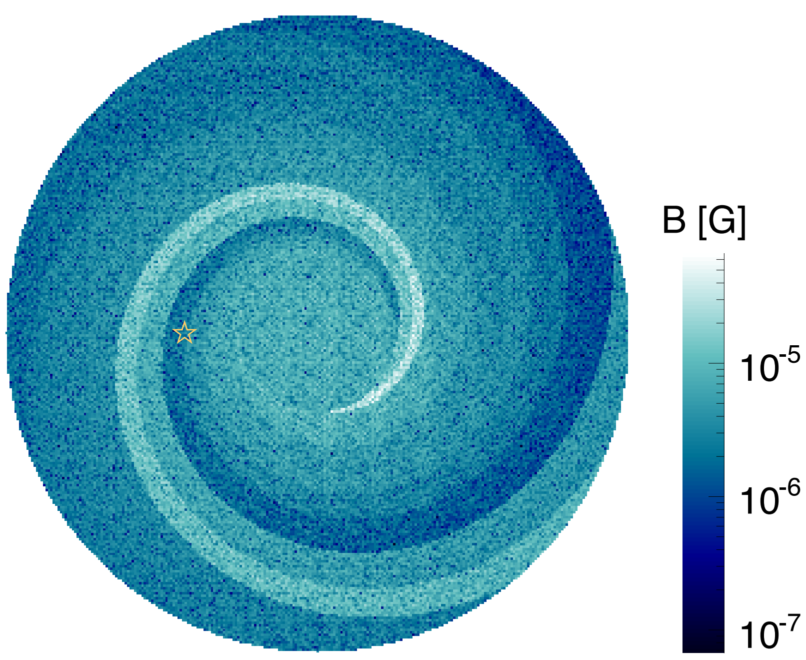
the galactic magnetic field

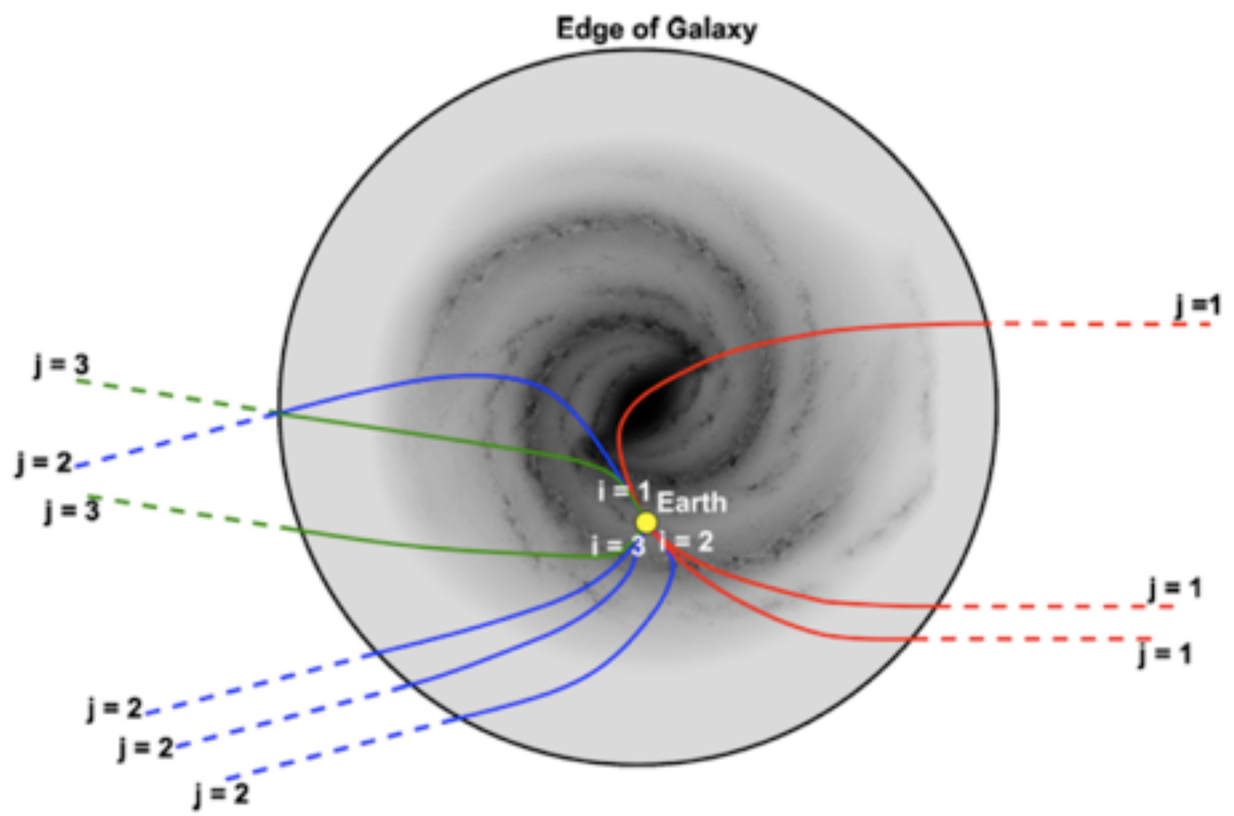
- assumes no energy losses
- each "lens" corresponds to a different energy bin
- lenses generated by backtracking protons to the galactic border
- nuclei have deflection of Z times the deflection for protons
- technique based on the PARSEC code (arXiv:1302.3761)
- these lenses are applied to simulated data a posteriori

Jansson & Farrar model - regular component



Jansson & Farrar model - total field





Jansson & Farrar, ApJ 761 (2012) L11

MHD details

- code has to conserve energy, momentum
- div(B) = 0
- no viscosity
- colisionless MHD
- cooling, heat and other energy terms
- grid-scale processes: chemical reaction, convection, ...
- subgrid-scale processes: formation/death of objects, stellar dynamo, feedback, ...

momentum density $$\vec{\pi} \equiv \rho \vec{v}$$

stress tensor $$\overleftrightarrow{T} \equiv \rho \vec{v} \otimes \vec{v} + \left(p + \frac{1}{2} B^2\right) \overleftrightarrow{I} - \vec{B} \otimes \vec{B}$$

total energy density $$\mathcal{H} \equiv \frac{1}{2} \rho v^2 + \frac{1}{\gamma - 1} p + \frac{1}{2} B^2$$

energy flow $$\vec{U} \equiv \left(\frac{1}{2} \rho v^2 + \frac{\gamma}{\gamma - 1} p\right) \vec{v} + B^2 \vec{v} - \vec{v}.\vec{B}\vec{B}$$

Y $$\overleftrightarrow{Y} \equiv \vec{v} \otimes \vec{B} - \vec{B} \otimes \vec{v}$$

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.\vec{\pi} = 0$$ conservation of mass

$$\frac{\partial \vec{\pi}}{\partial t} + \vec{\nabla}.\overleftrightarrow{T} = 0$$ conservation of momentum

$$\frac{\partial \mathcal{H}}{\partial t} + \vec{\nabla}.\vec{U} = 0$$ conservation of energy

$$\frac{\partial B}{\partial t} + \vec{\nabla}.\vec{Y} = 0$$ conservation of magnetic flux